TERMINAL RESEARCH REPORTS ON ARTIFICIAL LIMBS

COVERING THE PERIOD
FROM 1 APRIL 1945
THROUGH 30 JUNE 1947

COMMITTEE ON ARTIFICIAL LIMBS
NATIONAL RESEARCH COUNCIL

TERMINAL RESEARCH REPORTS ON ARTIFICIAL LIMBS

Fig. 1. Group of Committee Members, liaison personnel, staff, and subcontractors at Berkeley, California in July, 1946. Front Row, left to right: Dr. Verne T. Inman, Mr. Edmond M. Wagner, Mr. William C. Knopf, Dr. Philip D. Wilson, Dr. Paul E. Klopsteg, Dr. Robert R. McMath, Dr. Roy D. McClure, Mr. Tracy S. Voorhees, Mr. William C. Oliver. Second Row, left to right: Mr. John G. Catranis, Dr. John B. de C. M. Saunders, Commander T. J. Canty, Professor Kent Springer, Professor Howard D. Eberhart, Mr. Mieth Maeser, Dr. Rufus H. Alldredge, Dr. Miklós Hetényi, Professor S. F. Duncan, Major William H. Duke.

Fig. 2. Lonnie Carberry, bilateral above-elbow amputee, wearing Northrop arms.

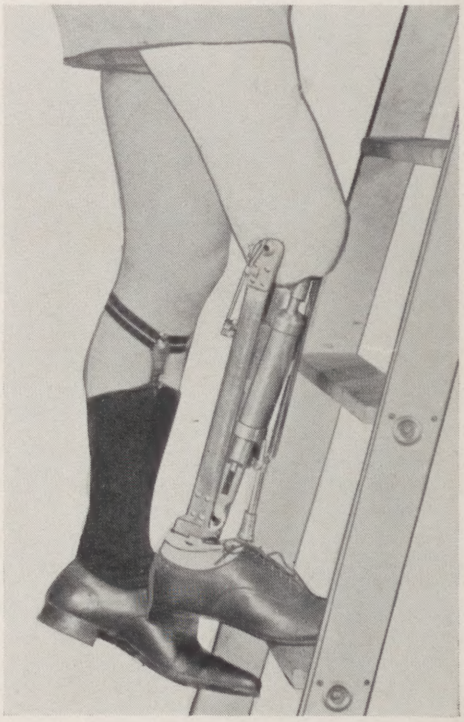


Fig. 3. An amputee descending a ladder wearing a Bradley-Catranis hydraulic above-knee leg.

TERMINAL

RESEARCH REPORTS ON ARTIFICIAL LIMBS

Report of the

Committee on Artificial Limbs

of The

National Research Council

Covering the Period, 1 April 1945

Through 30 June 1947

National Research Council

2101 Constitution Avenue, N. W.

Washington 25, D. C.

30 June 1947

CONTENTS

FOREWORD

This report is intended to review the work done in improving artificial limbs under the guidance of the Committee on Artificial Limbs of the National Research Council.

In the United States there are about 20,500 amputees whose disability is service-connected, of whom about 14,000 were in the Army and about 3,000 in the Navy in World War II. But during the period of the last war, some 65,000 civilians in war industries sustained injuries resulting in amputations, and the annual rate at which new amputees are added to the existing number is estimated at 40,000. The total number of amputees in our population is estimated to approach a half million, most of whom require artificial limbs. Hence the problem of improving such devices holds great possibilities, and is of great interest to a large segment of our population.

The Committee was originally established in April, 1945, as the Committee on Prosthetic Devices, operating under the Division of Medical Sciences and the Division of Engineering and Industrial Research, jointly, of the National Research Council. The history of the Committee and its activities covers a period of slightly more than two years. It began with the recognition in the Office of the Surgeon General of the Army and on the part of others that prosthetic appliances for veteran amputees needed improvement both functionally and structurally, and were susceptible of development in the esthetic sense insofar as artificial hands were concerned. It became the function of the Committee to organize and execute a technical program looking towards all needed improvements, so that veteran amputees might have available the best prostheses that it is practicable to provide. Funds for this work were made available under primary contracts between the National Academy of Sciences as the administrative agency and the Office of Scientific Research and Development, initially, and later the War Department and the Veterans Administration, respectively. The National Research Council is the operating agency for the National Academy of Sciences in carrying on the actual scientific and technological work involved in such a program.

The recommendation that a technical committee be established by the National Research Council developed out of deliberations in a meeting of representatives of numerous interested agencies held on the Chicago Campus of Northwestern University on 30 and 31 January, and 1 February 1945. The meeting was organized on the request of the

office of the Surgeon General of the Army by the Panel on Amputations of the Committee on Surgery of the Division of Medical Sciences, National Research Council, and was under the chairmanship of the chairman of that panel, Dr. Philip D. Wilson. In the discussions at that meeting, the suggestion emerged that much might be accomplished by a committee comprising surgeons with knowledge and experience in surgery relating to amputations, and physicists and engineers with knowledge of basic mechanics as well as materials, structures, and mechanisms. The committee that was appointed gave expression to this suggestion, although several months were required for the members to develop a working familiarity with both the anatomical and engineering aspects of the problems. It is believed that the work accomplished during its two years of activity could not have been accomplished either by surgeons alone or physicists or engineers alone.

In the initial stages of the work, various members of the Committee and operating staff visited the amputation centers of the Army and Navy, established contact with the American Limb Manufacturers Association (now the Orthopedic Appliance and Limb Manufacturers Association), and made visits to a number of the limb shops in the United States and Canada, both commercial and those connected with government hospitals. In the initial stages also it appeared desirable that there be liaison with the Veterans Administration, the Federal Security Agency, the National Bureau of Standards, the Army, and the Navy. Appointment of liaison representatives of these agencies was accordingly invited. Conferences were held with the National Foundation for Infantile Paralysis, the Pope Foundation, the Baruch Committee on Physical Medicine; and representatives of the Forest Products Laboratory, the National Inventors Council, and other agencies were consulted. Many industrial concerns were visited to gain additional background and information for the work. Among them were the Chrysler Corporation, General Motors, United States Rubber Company, Goodyear Tire and Rubber Company, Northrop Aircraft, Incorporated, Western Plastics, International Business Machines Corporation, du Pont Company, Bakelite Corporation, and Fafnir Ball Bearing Company.

The procedure adopted by the Committee was to have a subcommittee consisting of the surgeons appraise existing artificial limb structures and mechanisms, outline any faults and shortcomings, and suggest desirable functions and other features that might reasonably evolve in the course of development projects. The subcommittee of physicists and engineers was then to study the report of the surgeons, and following a careful analysis, prepare outlines of individual projects designed to accomplish the objectives set forth in the surgeons' report. In the meantime, the information that had been gained about various laboratories of commercial and other organizations permitted the Committee to select laboratories that appeared best suited to handle projects of a given type,

and then to proceed with negotiation of contracts with the several selected organizations to work upon the projects. Actual work began during the early summer of 1945. The first of the contractors to get under way was Northrop Aircraft, Incorporated, where some work in the field had already been undertaken independently at the instigation of the consulting surgeon of the Ninth Service Command, in cooperation with the Bushnell General Hospital in Brigham City, Utah. Other contracts were negotiated and became active in the ensuing months, as will appear in subjoined memoranda comprising this report.

All subcontracts were entered into with the understanding that a patent was to be secured on each device of merit developed under this program. In addition to a royalty-free license to the government, the clause provides that the Secretary of War or the Administrator of Veterans Affairs may designate manufacturers to whom must be granted nonexclusive, royalty-free licenses on patents for nongovernment use. These licenses are revocable upon like designation. This unusual and liberal licensing clause is testimony to the generous attitude of the subcontractors.

Another early activity of the Committee was to collect existing artificial limbs of all types and to keep them available at Committee headquarters at Northwestern University for staff engineers and Committee members as object material for technical studies of the mechanical and structural features of such devices. This was considered essential to guiding the course of research and development. Accordingly, numbers of samples were obtained of artificial hands, arms, legs, and feet from commercial manufacturers, from the Army and Navy limb shops, and from various other sources including limb manufacturers in Europe.

Further preparatory work consisted of assembling a reference library of medical and technical books and articles on amputation surgery and artificial limbs. Source material not available in its original form was procured in the form of microfilm copies. Articles of reference published in twelve foreign languages were translated into English and distributed to contractors as appeared necessary and desirable. The reference library also included a complete file of United States patents, obtained through the cooperation of the Commission of Patents, in the field of artificial limbs. Its first purpose was to provide a history and background of the state of the art as it appeared in the published patents. It further aided in clarifying the situation relative to any suggestions and ideas presented to the Committee, from the standpoint of the patent situation.

A rather general outline of the program of the Committee and its method of proceeding towards its objectives is summarized as follows:

a) To make a thorough study of existing prostheses and an analysis of their me-

chanical features with the aid of the aforementioned collection of artificial limbs and the reference library, including the patent file.

b) To conduct basic analytical studies of the mechanical functioning of both normal and artificial limbs.

c) To establish in the light of information gained in the studies mentioned under a) and b) a research and development program directed towards the improvement, simplification, and, so far as practicable, standardization in the design and construction of artificial arms and legs.

d) To conduct investigations of materials suitable for structures in limbs and parts of limbs and methods of fabricating them, and to design and construct models of mechanisms intended to accomplish as simply as possible the objectives set forth in the report of the subcommittee on surgeons.

e) To study the means and methods for securing prostheses to the body, holding them comfortably, and providing effective actuating arrangements. This includes such problems as designs of sockets and harnesses; and in the case of harnesses for arm prostheses, developing arrangements whereby the several functions of the arm and hand might be independently controlled.

f) To study methods of fitting with a view towards simplifying and standardizing the proper fitting of limbs to amputees and insuring the best possible adaptation of the prosthesis to the amputee's requirements, to correlate, insofar as this is possible, the work of the orthopedic surgeons and the limb fitters.

g) To consider the problem of the training of the amputee in the use of his prosthesis.

As the work of the Committee got under way, reports came from Europe through members of the Army Medical Corps who had returned from service in the European Theater that valuable work had been accomplished there in both amputation surgery and amputation prostheses. To ascertain with certainty the status of such developments, the Surgeon General of the Army appointed a commission which consisted of the Chief of Amputation and Prosthesis Unit and another officer of his staff, the chairman of this Committee, its staff surgeon and engineer, a recorder, and a photographer. This commission left for Europe by plane on 4 March 1946, and devoted about six weeks to its studies. The countries visited were Scotland, England, France, Germany, Switzerland, and Sweden. Much valuable information was gathered, which is set forth in detail in a lithoprinted document of 135 pages titled, "Report on European Observations," by the Commission on Amputations and Prostheses. The more important findings of the Commission pertained to the so-called cineplastic surgery as carried on by Sauerbruch of Berlin since about 1920 and in recent years improved by Lebsche of Munich; the suction socket

and its fitting to above-knee amputees; several mechanical developments in knee mechanisms that were observed in Sweden; and the methods of handling and training amputees at Queen Mary's Hospital, Roehampton, by the Ministry of Pensions. Training methods for leg amputees were also observed at the Kriegsschule in Munich. A meeting was held by the British Standing Advisory Committee on Artificial Limbs to which members of the Commission were invited, and asked to report on their observations on the continent. This report led to a decision by that Committee to send a commission to Germany for similar study. In making plans for this journey, the British commission secured substantial help from the American group. Since that time, the Standing Advisory Committee and the Committee on Artificial Limbs have regularly exchanged reports, and one of the members of the British Committee has attended a meeting of the Committee on Artificial Limbs. As a result of the observations in Europe, our Committee included in its program projects pertaining to cineplastic surgery, and to suction sockets.

It is appropriate to mention also that, following the establishment of this Committee, a similar committee was created by the National Research Council of Canada, and that close relationship and exchange of information have since been maintained between the two committees.

Before embarking on an elaborate program for the development of artificial arms and hands, the Committee realized, because of a lack of recent and authoritative information on the subject, that an exhaustive survey of patents, available literature, and previous models should be made, and that fundamental studies involving anthropometry, motion patterns, muscular action, and surgical procedures should be pursued to supply the necessary criteria for design.

With this background available to subcontractors working under the Committee's auspices, it became evident that sources of energy and methods of generating and transmitting force were of prime importance in the development of an artificial hand. Accordingly several lines of attack were followed using mechanical, hydraulic, and electrical means for force transmission. Improved mechanical arms using shoulder harnesses to actuate the hook or hand and to flex the elbow were designed, constructed, and service tested and now are available commercially. A functional mechanical work arm with a doubly wrapped spring elbow lock was evolved which was adapted to use many working tools. In the application of hydraulics one hand was developed using ankle flexion for its motive power while a hydraulic control unit to actuate hooks and hands is in the process of being completed. An electrically operated hand, to which the energy is supplied by miniature storage batteries carried around the amputee's waist, holds in pros-

pect ease of control and mobility particularly for shoulder disarticulation cases. The cineplastic artificial hand, which operates from pegs inserted through surgically constructed skin-lined muscle tunnels in the arm, or in the greater pectoral muscle, has given promise of materially improved function in hand prostheses for certain cases. Some improvement has been made in the arm and hand field by the use of force multipliers which have enabled the amputee to exert a stronger finger grasp than was possible previously.

Hand coverings, used to protect the complicated internal mechanisms of the hand, as well as to provide a natural appearance, have been improved and the new "cosmetic" gloves defy detection when casually seen beside a normal hand. Some research has been done also in an attempt to recover partially the sense of touch in the artificial hand, but so far this venture has not been completely successful. A major advance has been made in the construction of the artificial forearm and socket by the use of modern plastics and improved fitting methods. Standardization of certain mechanical parts of the arm, such as the wrist disconnect, should lead ultimately to simplified manufacturing procedures and reduced costs. Although much work has been done in the field of arm harnesses and suspensions, the final and most efficient design probably has not been reached.

In the field of lower extremity prostheses, extensive and exhaustive studies were made of the motions and actions of normal and artificial legs, ankles, and feet. Human locomotion and the mechanics of walking were investigated through the use of high-speed motion pictures of X-ray shadowgraphs of normal subjects, as well as through high-speed photographs of normal and amputated subjects to whose joints small light bulbs over the centers of rotation of the joints of the leg were attached. The field of view of the camera was interrupted at short time intervals so that the displacement patterns on the film of the camera appeared to be small lights moving along the path of each joint and flashing at short, equal time intervals. Measurements of force were made in various parts of the artificial legs, and the force with which the normal foot reacts with the ground was measured. From these data instantaneous centers of pressure of the normal person and of the amputee were computed accurately and improved leg designs were approached. The dissection of the human ankle revealed useful information as did the development and study of an artificial adjustable leg. As in the study of the hand, a review was made of existing literature, patents, and models, and anthropometric measurements were made on many subjects. Electromyographic studies were made of muscle actions in the leg, and an investigation is under way to seek the causes of deep-seated pain in the stump.

From the fundamental studies of lower extremities, it was learned that one outstand-

ing prerequisite for a normally acting artificial leg was the construction of a knee lock which would automatically lock or disengage at two distinct points in the walking cycle. Mechanical knee locks were demonstrated which were actuated by foot controls or by placing the amputee's weight on the stump socket. Hydraulic knee lock mechanisms, however, seemed to exhibit more practicality and there is evidence that a hydraulic knee lock which allows the artificial leg to approach closely the cadence and rhythm of the normal leg will be service tested soon.

Two artificial shanks, which showed significant improvement, were developed under Committee auspices. One was of crustacean type construction, fabricated out of a Fiberglas laminate impregnated with a low-pressure resin. This design has withstood satisfactorily all service and accelerated tests thus far. The other shank consisted of a Fiberglas laminate cylindrical tube impregnated with a modified phenolic resin and surrounded by a lightweight cellular cellulose acetate covering which duplicated the contour of the normal leg and was covered by a rubber-like material which looked and felt about like the natural flesh.

Two rubber ankle mechanisms have been constructed, each of which reproduced the normal ankle action with reasonable faithfulness and protected the artificial leg and the amputee from shock by a cushioning action. As a result of the ankle dissection studies, an experimental, adjustable mechanism which permitted limited rotation about the artificial shank, was designed and constructed. By the use of this ankle rotation mechanism, improvement in the subject's gait was observed and the amputee reported immediate improvement and comfort due to a marked reduction of irritation and pain at the ischial seat.

One of the most significant developments in the artificial leg field has been the reintroduction in this country of the method of securing the limb to an above-knee stump by suction or atmospheric pressure. It is referred to as the "suction socket." This has eliminated the necessity for wearing cumbersome harnesses and belts and has given the amputee a greater feeling of security. Although the service tests on this method of fitting have not been completed, indications are that the suction socket method of fitting will be a vast improvement for above-knee amputees with suitable stumps.

A new mechanical method for fitting sockets has been investigated, which, although thus far has been applied satisfactorily only to below-knee stumps, shows promise in the fitting of above-knee amputees as well. This system, based on the "dilatancy" principle, consists of molding a positive replica of the stump in a negative mold, the latter formed by pouring small glass particles around the stump and then solidifying the mass by removing the air surrounding the glass beads. From this positive replica the socket is formed.

A program of mechanical tests, laboratory tests, and service tests has been undertaken by the Committee. Several leg testing machines and hand and arm testing machines have been developed and put to use. Also standards have been established covering the field of plastics for the artificial limb industry. This comprehensive program of testing has aided greatly in expediting final approval by the Committee of developed products in order that these devices might be manufactured commercially and made available to the public.

In the memoranda to follow there are presented brief factual statements relative to the personnel of the Committee and of members of the staff and the changes that occurred from time to time. There are included also statements regarding the liaison personnel, the location of cooperating agencies with testing facilities, and a list of dates and locations of meetings of the Committee, together with scientific exhibits of developments carried on under Committee auspices, and locations and dates of symposia of contractors with members of the Committee and its staff. Following these presentations, there is an exhibit of the research and development program as actually carried out in the projects under contract with the various laboratories that participated in the program.

As the projects and contractors increased in number, the operating details became increasingly burdensome to the Committee, and particularly to the chairman's office. It was therefore decided in the autumn of 1946 to place the operating responsibility on an executive director, who should be located in Washington. This plan was followed, and the Committee was fortunate in being able to engage the services of Brigadier General F. S. Strong, Jr., whose separation from military service had occurred several months earlier. The shift in the base of administrative operations proved valuable, particularly in view of the fact that the requesting agencies have their headquarters in Washington. Some of the complicated problems involved in interrelationships among government agencies and an organization such as the Committee on Artificial Limbs could have been handled only with exereme difficulty had not the office been in Washington. General Strong and his staff deserve great commendation for the manner in which they systematized the work and carried it towards conclusion.

Although a committee of the National Research Council cannot under the charter of the Council function in any capacity other than as a scientific and technological body, the Committee on Artificial Limbs was frequently regarded by high government officials, including members of Congress, and by representatives of the press, veterans' organizations, and other nongovernmental agencies as an organization commissioned to provide new prostheses for amputees. Influential—though unfortunately uninformed—individuals occasionally put the Committee under considerable pressure to do things which it was not authorized to do. These individuals did not realize that the Committee's function

was purely technical and that it made suggestions based on experimental investigations upon which requesting agencies might act to bring the suggested improvements to practical form. Moreover, the Committee was on several occasions made the target of criticism for failure to do things which were not contemplated in its original assignment. Difficult as the assignment was, it was made more difficult by the attitudes and pressures described, and it appeared that the only corrective for such situations was to find the services of a man experienced in public relations through whom uninformed officialdom and others might be educated as to the true functions of the Committee. The Committee was fortunate, indeed, in securing the voluntary services as consultant on public relations of Colonel Robert S. Allen, whose advice and guidance in these matters proved highly valuable. Through Colonel Allen's efforts and contacts, it also became possible to present results of work done under Committee auspices to a congressional committee, the Administrator of Veterans Affairs, the Secretary of War, and the President of the United States, and to give a demonstration before a meeting of the American Society of Newspaper Editors.

Throughout the period of activity of this Committee, it was fortunate in having the consulting services of Dr. Charles F. Kettering. His extensive knowledge of materials and methods, and his wide acquaintance and experience in industry proved most valuable in the saving of time and in the development of helpful contacts.

At its meeting in Washington on 21 April 1947, the Committee carefully reviewed the status of all of its projects and came to the conclusion that with few exceptions the underlying scientific and technological work had been completed. It accordingly recommended that its services be terminated as of 30 June 1947 and that the results of its activities be transmitted in detail to the Veterans Administration, now the principal requesting agency, and that the further engineering development and "reduction to practice" become the responsibility of the Veterans Administration. An agreement was reached by the interested agencies that this be the procedure. As of 1 July 1947 the Veterans Administration is carrying the work forward with such assistance as may be desired from the National Research Council, based upon the experience of the Committee on Artificial Limbs, of individual members of the Committee, and of the staff. Certain projects are being consolidated, and the most promising results of the various developments are being carried forward by several qualified contractors. Data amassed on the subject of artificial limbs will be available through the medium of microfilm and excerpts from subcontractors' final reports to those concerned with the problem. It may be expected with some confidence that this activity will result in the availability

of proved and practicable devices, first to veterans and later through regular commercial channels to any civilian amputee needing such devices.

Members of the Committee gave freely and generously of their time, and contributed much out of their wide experience. Their compensation for the effort put forth will be derived from the satisfaction in accomplishments from which thousands of persons with physical handicaps may derive benefit.

To Mr. William C. Knopf, technical assistant to the chairman, much credit is due for able accomplishment in digesting and summarizing the final project reports of subcontractors, and for organizing and editing this report as a whole.

For the Committee:

Paul E. Klopsteg, Chairman

ORGANIZATION

For the purpose of administering a research and development program in the field of prosthetic and sensory devices, the National Research Council* established the "Board for Prosthetic and Sensory Devices" under which there were two technical committees appointed: the Committee on Prosthetic Devices and the Committee on Sensory Devices. Within the National Research Council, the Division of Medical Sciences and the Division of Engineering and Industrial Research were responsible jointly for the activities of the Board for Prosthetic and Sensory Devices and for its two committees. Later the Board for Prosthetic and Sensory Devices was dissolved, permitting the Committee on Prosthetic Devices to report directly to the National Research Council. Later also the name of the Committee was changed to "Committee on Artificial Limbs." The following organization roster lists the personnel of the Board and the Committee together with representatives of other organizations directly concerned with the Committee's work.

*The National Research Council is a technical body within the National Academy of Sciences charged with the responsibility for "conducting research in the mathematical, physical, and biological sciences, and in the application of these sciences to engineering, agriculture, medicine and other useful arts." The National Academy of Sciences and the National Research Council are quasi-government agencies. Their research work is financed by the returns from endowment funds, by special grants, and by contracts with other agencies.

Board for Prosthetic and Sensory Devices[1]

Headquarters:
Suite 355
Northwestern Technological Institute
Evanston, Illinois

Dr. Paul E. Klopsteg, Chairman
Director of Research
Northwestern Technological Institute
Evanston, Illinois

Dr. Oliver E. Buckley
President, Bell Telephone Laboratories
New York, New York

Dr. George W. Corner
Director, Department of Embryology
Carnegie Institution of Washington
Baltimore, Maryland

Dr. Roy D. McClure[2]
Surgeon-in-Chief
Henry Ford Hospital
Detroit, Michigan

Dr. Charles F. Kettering, Consultant[3]
Vice-President and Director of Research
General Motors Corporation
Detroit, Michigan

Dr. Miles J. Martin, Secretary

1. Dissolved in November, 1946.

2. Originally Consultant to the Committee on Prosthetic Devices; became a Member of the Committee in July, 1946.

3. Also Consultant to the Committee on Prosthetic Devices.

Committee on Artificial Limbs[4]

Chairman

Dr. Paul E. Klopsteg
Director of Research
Northwestern Technological Institute
Evanston, Illinois

Members

Dr. Harold R. Conn
Surgeon-in-Chief
Goodyear Tire and Rubber Company
Akron, Ohio

Dr. Miklós Hetényi[5]
Professor of Engineering Mechanics
Northwestern University
Evanston, Illinois

Dr. Roy D. McClure
Surgeon-in-Chief
Henry Ford Hospital
Detroit, Michigan

Dr. Robert R. McMath
Professor of Solar Physics
University of Michigan
Pontiac, Michigan

Mr. Mieth Maeser
Research Engineer
United Shoe Machinery Corporation
Beverly, Massachusetts

Dr. Paul B. Magnuson[6]
Professor of Bone and Joint Surgery
Northwestern University Medical School
Chicago, Illinois

Dr. Philip D. Wilson
Clinical Professor of Orthopedic Surgery
Columbia University
New York, New York

4. Formerly Committee on Prosthetic Devices.

5. Replaced Mr. E. M. Wagner as Member of the Committee in July, 1946.

6. Also Liaison Officer between CAL and the Veterans Administration, Washington, D. C. Dr. Magnuson resigned as a Member of the Committee in April, 1947, because of his many duties as Acting Assistant Medical Director for Research and Education of the Department of Medicine and Surgery of the Veterans Administration.

Consultants

Mr. Robert S. Allen
Washington Bureau
1204 National Press Building
Washington, D. C.

Dr. Charles F. Kettering
Vice-President and Director of Research
General Motors Corporation
Detroit, Michigan

Staff

Headquarters:
2503 Munitions Building
Washington, D. C.

Mr. Frederick S. Strong, Jr.
Executive Director

Dr. Rufus H. Alldredge[7]
Staff Surgeon

Mr. Leroy R. Barrett[8]
Field Engineer

Mr. Robert A. Bowman, Jr.
Assistant Staff Engineer

Mr. Tonnés Dennison
Special Assistant to Mr. Strong

Mr. C. Richard Fadely
Staff Limb Fitter

Mr. Carlton E. Fillauer[9]
Staff Limb Fitter

Mr. William C. Knopf[10]
Technical Assistant to Dr. Klopsteg

Mr. Lorrin H. Madsen[11]
Staff Limb Fitter

Mr. Eugene F. Murphy
Staff Engineer

Mr. Walter E. Thwaite, Jr.
Field Engineer

Mr. Edmond M. Wagner[8]
Chief Engineer

Commander August Dvorak, USNR
Field Assistant on loan from the U. S. Navy

7. Resigned in February, 1947, and became part time consultant to CAL.

8. Located at 2171 Colorado Boulevard, Los Angeles, California. This office was closed as of 30 June 1947.

9. Resigned in December, 1946, and became part time consultant to CAL.

10. Formerly Executive Secretary of CAL, replacing Dr. Miles J. Martin who resigned in August, 1946. Mr. Knopf is located in the Northwestern Technological Institute, Evanston, Illinois.

11. Resigned in March, 1947.

Liaison Personnel with CAL

Colonel William S. Stone
Office of the Surgeon General, U. S. Army

Colonel R. G. Prentiss[12]
Office of the Surgeon General, U. S. Army

Major William H. Duke[13]
Office of the Surgeon General, U. S. Army

Colonel Leonard T. Peterson[14]
Office of the Surgeon General, U. S. Army

Dr. Paul B. Magnuson
Veterans Administration

Dr. Detlev W. Bronk
Chairman, National Research Council

Dr. Lewis H. Weed
Division of Medical Sciences, National Research Council

Dean Frederick M. Feiker
Division of Engineering and Industrial Research, National Research Council

Dr. Philip S. Owen
Division of Medical Sciences, National Research Council

Mr. Louis Jordan
Division of Engineering and Industrial Research, National Research Council

Mr. George D. Meid
National Academy of Sciences

Mr. Bernard L. Kropp
National Academy of Sciences

Mr. Tracy S. Voorhees
Representative of the Secretary of War

Captain Frank P. Kreuz
Bureau of Medicine and Surgery, U. S. Navy

Captain Howard H. Montgomery[15]
Bureau of Medicine and Surgery, U. S. Navy

Dr. Henry H. Kessler
Office of Vocational Rehabilitation

Mr. William F. Roeser
National Bureau of Standards

Dr. R. I. Harris
Department of Veterans Affairs
Ottawa, Canada

Dr. J. Craft
Ministry of Pensions
Limb Fitting Center
Queen Mary's Hospital
Roehampton, London, England

12. Served as unofficial liaison officer during the summer of 1946.

13. Replaced by Colonel Stone in September, 1946.

14. Replaced by Major Duke in May, 1946, upon separation from the service.

15. Replaced by Captain Kreuz in April, 1946.

Testing Facilities

Army Prosthetics Research Laboratory
Washington, D. C.

Laboratories of CAL Subcontractors

National Bureau of Standards
Washington, D. C.

Percy Jones General Hospital
Battle Creek, Michigan

Thomas M. England General Hospital
Atlantic City, New Jersey
U. S. Naval Hospital
Mare Island, California
U. S. Naval Hospital
Philadelphia, Pennsylvania
Veterans Administration Testing and Development Laboratory
New York, New York
Walter Reed General Hospital
Washington, D. C.

MEETINGS

Meetings of the Committee are held at the call of the Chairman. The following is a list of meetings that have been held:

First Meeting, National Academy of Sciences, Washington, D. C., 26 March 1945.

Second Meeting, National Academy of Sciences, Washington, D. C., 16 April 1945.

Third Meeting, Henry Ford Hospital, Detroit, Michigan, 14 and 15 May 1945.

Fourth Meeting, Committee Headquarters[16], Evanston, Illinois, 12 June 1945.

Fifth Meeting, Thomas M. England Hospital, Atlantic City, New Jersey, 16 July 1945.

Sixth Meeting, National Academy of Sciences, Washington, D. C., 10 October 1945.

Seventh Meeting, Boston, Massachusetts and at United Shoe Machinery Corporation, Beverly, Massachusetts, 28 and 29 November 1945.

Eighth Meeting, Northwestern University, Chicago Campus, Chicago, Illinois, 16 and 17 January 1946.

Ninth Meeting, New York, New York, 27 February 1946.

Tenth Meeting, National Academy of Sciences and Walter Reed General Hospital, Washington, D. C., 14 and 15 May 1946.

Eleventh Meeting, Fairmont Hotel, San Francisco, California, 9 July 1946 and Chapman Park Hotel, Los Angeles, California, 11 July 1946.

Twelfth Meeting, National Academy of Sciences, Washington, D. C., 1 and 2 October 1946.

Thirteenth Meeting, Veterans Administration, Washington, D. C., 6 and 7 December 1946.

Fourteenth Meeting, Palmer House, Chicago, Illinois, 29 January 1947.

Fifteenth Meeting, National Academy of Sciences, Washington, D. C., 21 April 1947.

16. Headquarters moved to Washington, D. C., 1 December 1946.

SCIENTIFIC EXHIBITS

San Francisco, California, 1-5 July 1946, sponsored by the American Medical Association.

Minneapolis, Minnesota, 7-9 October 1946, sponsored by the American Limb Makers' Association.

Chicago, Illinois, 27-29 January 1947, sponsored by the American Academy of Orthopedic Surgeons.

SYMPOSIA

Chicago, Illinois, 16-17 January 1946. This meeting was attended by Members of the Committee, subcontractors, and members of the military services for the purpose of discussing the progress of the work of the Committee.

San Francisco, California, 8 July 1946. This was a general discussion of the program by Members of the Committee and the subcontractors.

Washington, D. C., 26 August 1946, Walter Reed Hospital; 27 August 1946, National Academy of Sciences; Battle Creek, Michigan, 30 August 1946, Percy Jones General Hospital; Evanston, Illinois, 31 August 1946, Northwestern University. These meetings were attended by orthopedic surgeons for the purpose of discussing the cineplastic program. Demonstrations were given by three German amputees.

Berkeley, California, 18-21 November 1946. This symposium held at the University of California was attended by persons interested in the study of the mechanics of walking.

Hawthorne, California, 10-12 February 1947. This meeting held at Northrop Aircraft, Inc. was to discuss problems pertinent to the development of artificial arms and hands.

Pittsburgh, Pennsylvania, 6 March 1947. This conference held at the Mellon Institute of Industrial Research was for the purpose of discussing the work on cosmetic hands and cosmetic coverings.

Berkeley, California, 21 March 1947. A meeting to discuss the suction socket program was held at the University of California, attended by those closely connected with the program.

Los Angeles, California, 28 March 1947. This conference was for the purpose of discussing the cineplastic personnel and devices, and was held at the Sawtelle VA Hospital.

Washington, D. C., 14-18 April 1947. This was a general display and evaluation of all projects and developments under the auspices of the Committee on Artificial Limbs.

Burbank, California, 16-17 June 1947. This meeting was for the purpose of evaluating the developments in lower extremity prostheses.

NORTHROP AIRCRAFT, INCORPORATED

Hawthorne, California

BACKGROUND. Early in 1944, Mr. John K. Northrop, President of Northrop Aircraft, Incorporated, became interested in the rehabilitation work being carried on at the Birmingham General Hospital in Van Nuys, California. One department of this hospital employed patients to work on bench subassembly at regular hourly wages while convalescing. Mr. Northrop realized that the use of modern materials and skills could increase the productivity and caliber of the work being done and should result in benefit to the amputees employed.

His first step was to design a cable control which replaced leather thongs to operate the artificial arm. Plastics then were introduced to replace wood and leather sockets, and design of a new wrist mechanism was being undertaken when the Committee on Artificial Limbs invited Northrop Aircraft, Incorporated to participate in its research and development program.

Work under Committee sponsorship started in June, 1945, with the general improvement of artificial arms, hands, hooks, controls, and legs as its goal. This program stressed a practical rather than theoretical solution of problems and several amputees were used continuously as test personnel. The program began under the able guidance of Mr. Meyer Fishbein as project engineer. Mr. Gilbert Motis became engineering supervisor in early 1947 when Mr. Fishbein was transferred to another project, and Mr. F. M. Gibian became the project manager.

Although a development program on artificial limbs still is being carried on at Northrop Aircraft, Incorporated through a program financed directly by the Veterans Administration and the War Department, the program sponsored by the Committee on Artificial Limbs ended June, 1947, with the successful completion and service testing of several devices for the amputee which are described below.

PROJECTS. ***(1) Artificial Arms.*** *(a) Below-elbow Arms.* In designing below-elbow artificial arms rotation at the wrist of the prosthesis was achieved by taking advantage of the natural rotation of the forearm stump. This pronation and supination of the hook or hand improved the usefulness of the arm in most operations and in addition, provided exercise for the forearm muscles which the conventional prosthesis did not allow.

The below-elbow arm, Fig. 4, is shown sketched in its entirety illustrating its internal mechanism. The hook or hand was controlled by a stainless steel cable enclosed in a stainless steel wire wound casing, the latter was attached to the forearm and to the upper arm cuff by suitable rotating retainers. Operation of the hook or hand is accomplished by a forward movement of the shoulder opposite the amputation. The wrist rotation mechanism contained a planetary gear step-up system which increased the amount of rotation available in the hook or hand from the stump in a ratio of approximately 2.3 to 1. It also contained a locking mechanism which resisted a twisting load in the hook or hand, thus taking the support of such a load off the stump. This allowed the stump to be relaxed after positioning, and since it required no special effort to operate, saved energy. Since the wrist pronation-supination mechanism is a desirable feature for below-elbow amputees, much time and effort was required during service tests to eliminate defects in the roller lock. Loads created at the roller were much higher than anticipated, but finally a wrist lock was engineered satisfactorily to correct the excess slippage at the wrist. Many other rotational wrist lock units were designed and installed in below-elbow arms

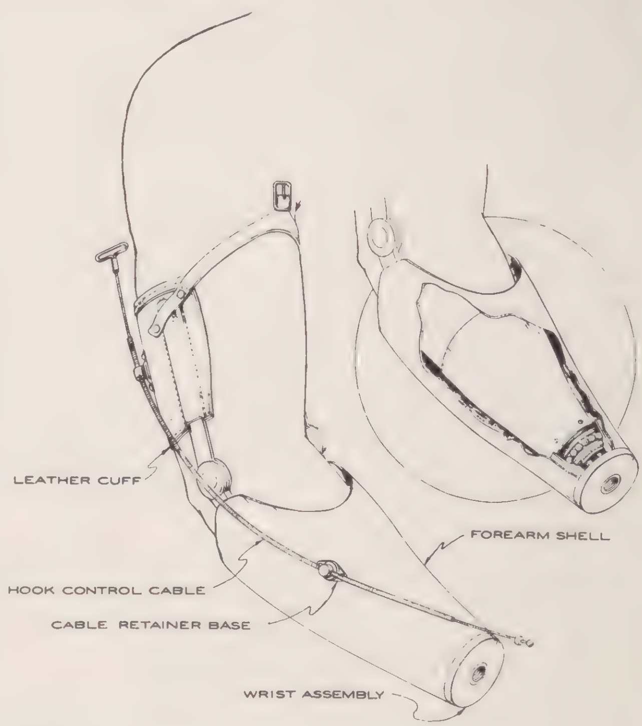


Fig. 4. Northrop below-elbow arm.

Fig. 5. Wrist disarticulation arm with cutaway view.

and given trial tests by amputees before this final model was decided upon.

The entire wrist unit was assembled outside of the arm and placed through the outer shell into its mating part in the forearm. Set screws held this entire assembly in place and could be removed easily.

A modified arm for wrist disarticulation cases was designed and service tested on amputees. A wrist disarticulation provides almost normal wrist rotation without the use of any mechanical device other than a laminated plastic socket, and in Fig. 5, this arm is shown with a cutaway view of the socket showing the threaded insert for the hook attachment which was molded into the end of the socket. The harness, shown on a bilateral below-elbow amputee, Fig. 6, was made up of two bands of tape attached to the opposite sides of the socket and carried through a cross-over pad located on the rear side of the upper arm. This pad was attached to the harness by two tapes which jointed together just below the shoulder in the front and passed around each side of the arm to the pad on the rear of the upper arm.

Another addition to the below-elbow arm field was the design of a wrist rotation arm with cineplastic control of the hand. This arm, shown in Fig. 7, was constructed of plastic laminates and is similar to the regular Northrop below-elbow arm with wrist rotation except for the changes and additions in the design necessary to make use of pins through the skin-lined muscle tunnels to actuate

Fig. 6. Bilateral wrist disarticulation showing harness arrangement.

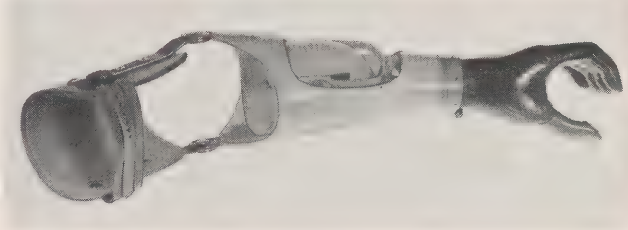


Fig. 7. Northrop below-elbow cineplastic arm.

Fig. 8. German amputee wearing Northrop cineplastic prosthesis on his right arm.

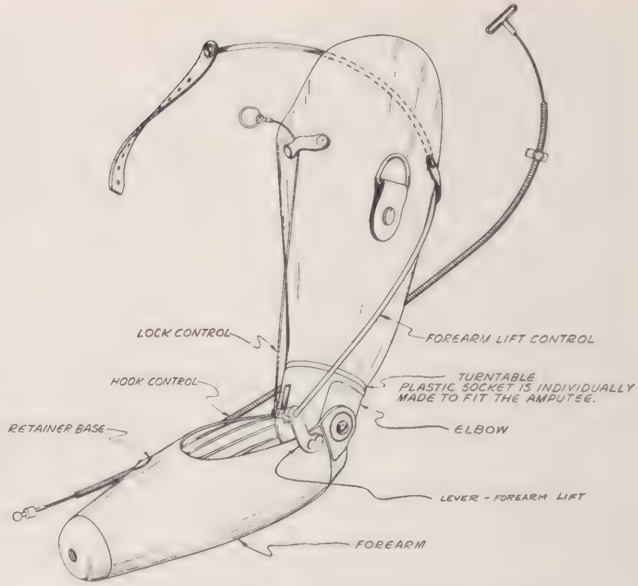


Fig. 9. Above-elbow arm for a unilateral amputee.

the fingers and thumb. Because this development was performed on a German amputee brought to this country to act as a subject to aid in developing a better prosthesis, the standard Hüfner (German) hand which he had brought with him was used. It was carved of wood and was light in weight. Confinement of the muscle tunnel pins to the slot guides which parallel the muscle travel transmitted torsional motion to the stump socket and prevented a loss of motion. A manually operated lock included a force multiplier to increase the grip when locking the fingers in any position. The German amputee, shown in Fig. 8, is wearing the Northrop cineplastic arm with wrist rotation control on his right arm and is wearing a German-made prosthesis on his left arm. The German prosthesis makes manual supination and pronation of the hand necessary.

In a further study of cineplastic control of hands, a below-elbow wrist disarticulation arm with cineplastic control was designed and constructed.

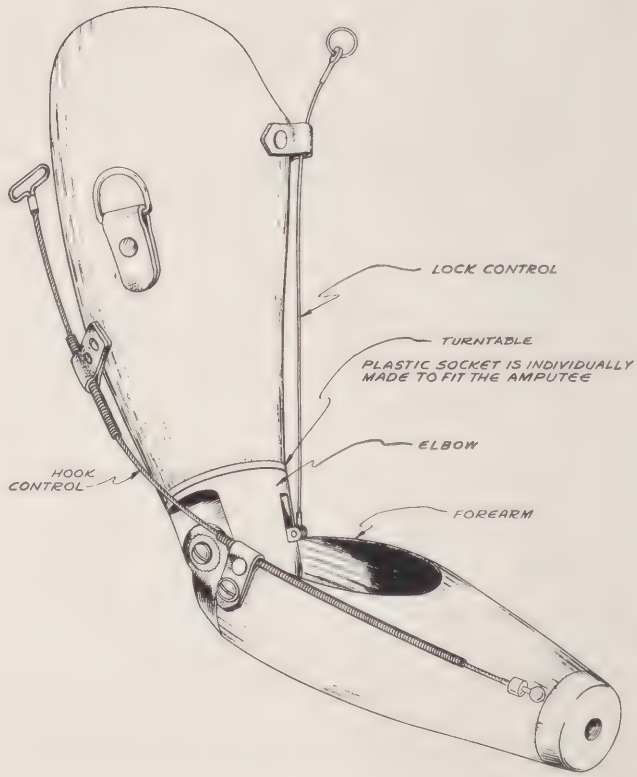


Fig. 10. Above-elbow arm for a bilateral amputee.

(b) Above-elbow Arms. There were two similar types of above-elbow arms with elbow locks developed by Northrop Aircraft, Incorporated. The first, shown in Fig. 9, is a design for the unilateral amputee and differs in its control system from the arm shown in Fig. 10, which was designed for the bilateral amputee. With each arm it is possible for the amputee to use the hook in pracically all positions obtainable with the sound, natural arm.

The hook control for these arms is a stainless steel cable enclosed in a stainless steel flexible casing as in the below-elbow arm. Several types of elbow mechanisms were tested on amputees, but the voluntary elbow lock used with the uncoupled arm was accepted by the amputees as being the most desirable. This elbow locking mechanism was enclosed in an aluminum alloy housing at the elbow joint and was actuated by a downward shrug of the shoulder associated with the arm. Alternate shrugs were used to lock and unlock the elbow. The device contains a friction mechanism as protection against excessive forearm loads.

The method used for lifting the unilateral forearm differs from that used on the bilateral arm. The unilateral amputee exerts a forward motion of the stump which pulls against a cord to raise the forearm. On the bilateral amputee, the forward stump motion pulls against the hook control cable, which was designed to lift the forearm unless the elbow is locked. If the elbow is locked the hook opens by the usual shoulder shrug. The elbow turntable is a friction plate made of plastic material and located in the upper arm just above the elbow joint. It is operated manually and the friction may be adjusted easily with four screws in the upper arm socket.

The design of the present Northrop above-elbow arm involved the consideration of many types of attaching harnesses and operating means. Although experience has indicated that most amputees enjoy the freedom that is possible with the uncoupled arm with a passive elbow lock, described above, a fully coupled type arm, Fig. 11, of the cable and pulley type forearm lift coupling was tested. Another fully coupled forearm lift utilized a push-pull rod to eliminate the delicate coordination between the two cables necessary in the cable and pulley type forearm lift.

A friction type elbow lock consisting of eleven intermeshing discs, showed some promise, but was not efficient enough to prevent slippage when operated by the small input forces from the harness. A cone clutch elbow lock, Fig. 12, was designed to reduce the compression load necessary to create sufficient friction in a clutch type unit. While preliminary models were not completely satisfactory, further designs are to be carried out using this principle in an effort to make a simple and a more efficient elbow lock.

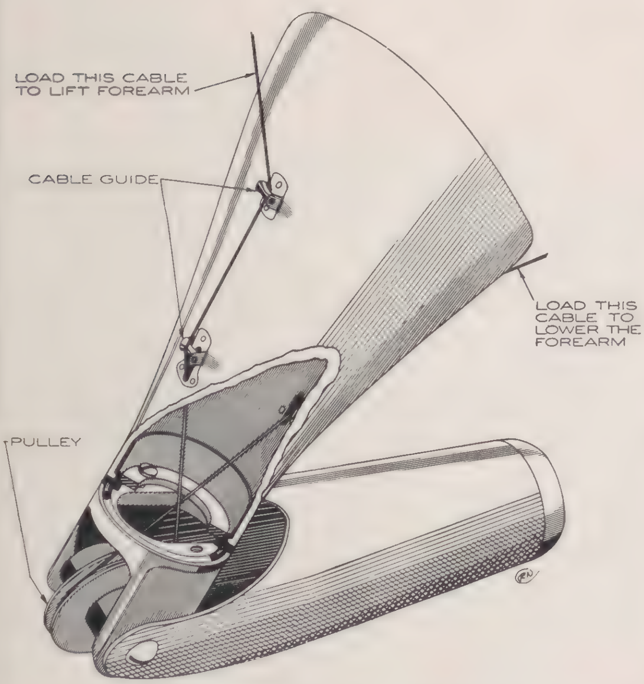


Fig. 11. Northrop above-elbow fully coupled arm.

Fig. 12. Close-up of cone clutch type elbow lock.

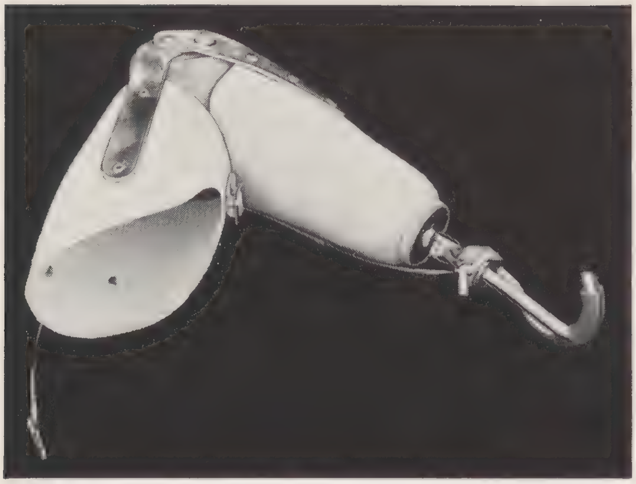


Fig. 13. Arm with polycentric elbow joint for short forearm stumps.

Fig. 14. Arm with modified elbow lock for shoulder disarticulation cases.

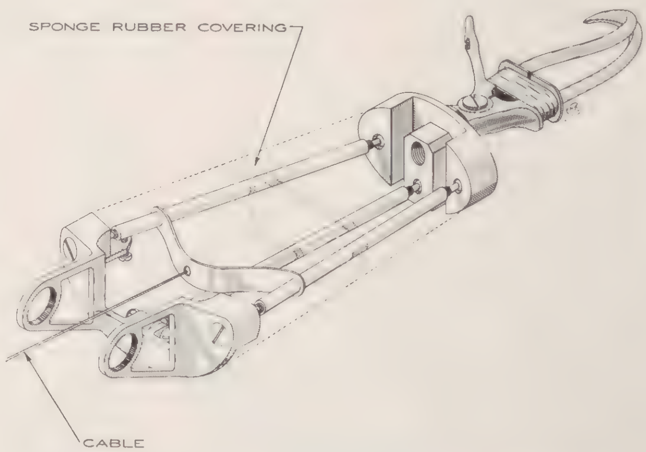


Fig. 15. Three-rod above-elbow forearm with wrist flexion and rotation.

A polycentric elbow joint is shown in Fig. 13, as a means of using the available power and travel of a very short below-elbow amputation to its best advantage. A stump socket cap is pivoted at the elbow joint on hinges attached to an upper arm cuff and motion is transmitted through levers to the forearm in ratios of 2-to-1 or 3-to-1 which increases the available motion.

For some shoulder disarticulation cases, unable to operate the regular Northrop type elbow lock by the downward shrug of the shoulder because of the rigid condition caused by the shoulder cap socket, a modified elbow lock, Fig. 14, was designed. This lock was reversed so that the control lever projected behind the elbow rather than in front and a ball knob and extension lever enabled the amputee to operate the lock by a downward push of the elbow on a table or on his own person.

A study of the motions of the normal arm indicated that forearm lift and wrist rotation often were used in conjunction with each other. Because such operations, such as eating, would become simpler and easier for the above-elbow amputee by coupling these motions together, several experimental models were made incorporating coupled forearm lift rotation with wrist flexion. One of these which is shown in Fig. 15, is an above-elbow three rod type arm which is an attempt to duplicate the natural motions of the bones of the arm. This three rod forearm utilizes the same type of motion as the radius and ulna of the natural forearm; the third rod was used to stabilize lateral movement of the arm since the other two rods have ball type ends. A flat spring was attached to the radius and ulna bone rods about two inches below the elbow and a pull on the cable attached tends to force the rods together and as they cross the wrist end rotates about the axis of the stabilizing rod. So far difficulty has been met in stabilizing this rod type forearm. Other methods of wrist rotation, not involving the use of rods, are being investigated.

(2) Artificial Hands. One of the experimental hands developed under this project is shown in Fig. 16, without its palmar section and foam rubber covering and cosmetic glove. This hand operates from a center control rod and can be disconnected quickly from the artificial forearm. The hand can be operated by cineplastic muscle tunnels or by shoulder shrugs and is designed to grasp an irregularly shaped object with an equal force from each finger. The thumb must be positioned manually in either the open or the partially closed position, and may be rotated about the thumb operating mechanism from a position in the plane of the palm to a position at right angles to the palm.

A hand using leaf spring type fingers, Fig. 17, was designed in an attempt to permit bending at natural joints and to grasp irregularly shaped objects. Cables from each fingertip, running through the guides to cable drums at the base of each finger, give a natural movement to the fingers. The thumb is a solid piece without joints and is positioned manually in three places about the center line of the worm drive gear. In its present state of development, the fingers of this hand are unstable under load and the mechanism is complicated and subject to jamming. The hand has advantages, however, of natural movements and light weight combined with the ability to grasp irregularly shaped objects.

Another hand, Fig. 18, was designed for the sole purpose of determining the need for a flexible palm capable of cupping, as does the natural hand when passed through a small opening such as a shirt sleeve. The fingers are of a cable-actuated leaf spring type with plastic guide blocks attached to the springs between the joint locations. From the fingers the actuating cables pass through fine closely wound springs and tie together at the center of the quick wrist disconnect to give center control. The thumb is without joints and may be positioned in opposition to the fingers before the hand covering is installed. The simplicity of this hand design is its main feature and its failing is found in the instability of the fingers under a medium load. Additional investigation seems to be warranted to improve this design to fill the need for a lightweight, simple, easily produced, low cost hand.

In conjunction with the research on hands, considerable effort was made toward the design of improved finger mechanisms. A pivoted link finger with a cord drive was bench tested as was a link drive finger, which transmitted motions easily and was simple to fabricate. A hydraulic finger also was constructed consisting of a rubber bladder encased in a wound spring sheath to limit radial expansion without effecting lineal expansion.

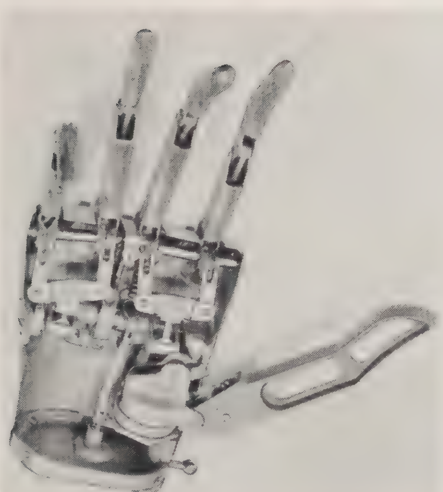


Fig. 16. Experimental hand mechanism with center control rod.

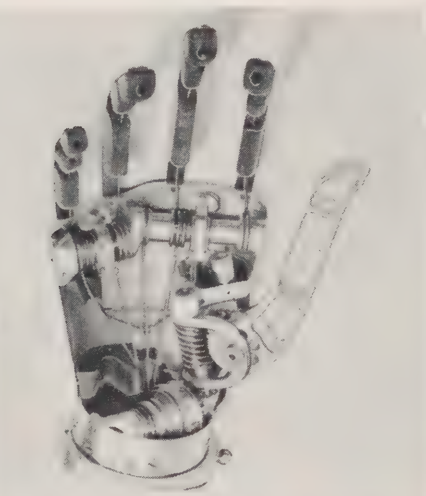


Fig. 17. Cable controlled, leaf spring mechanical hand.

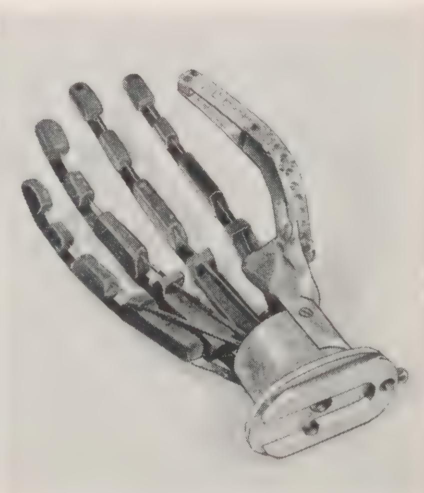


Fig. 18. Experimental flexible palm mechanical hand with quick wrist disconnect.

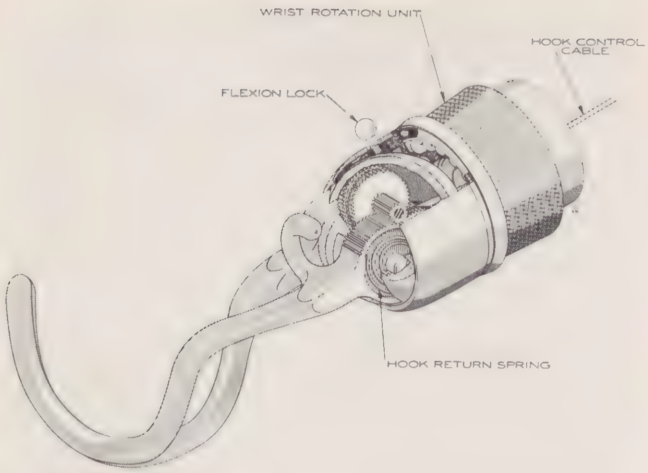


Fig. 19. Scissors type gear driven hook with central cable control.

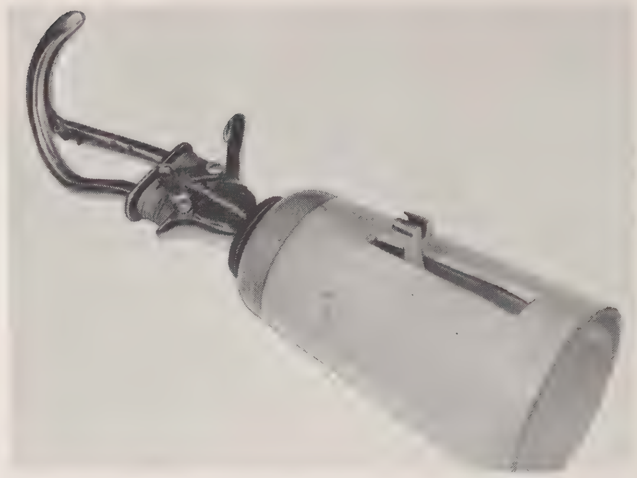


Fig. 20. Modified centrally controlled hook with link mechanism.

(3) Hook Design. In an approach to the problem of hook design, Northrop Aircraft engineers attempted to supply more versatility in the hook for the amputee by using force multipliers to increase the gripping force, locking controls to maintain the desired grip, and center control of the hook along the arm axis to allow easy removal with a quick-disconnect device.

A lightweight scissors hook, Fig. 19, first was tried which consisted of gears actuated by a cable to move the fingers away from each other. A spiral wound spring returned the fingers to the closed position when tension on the cable was released. One outstanding objection to the use of this hook was that a large cable force of ten pounds was needed to open the fingers compared to the grip at the finger ends of only three pounds of force. The amputees using this hook criticized its lack of a fixed finger which could be used as a reference point for picking up an object.

Next, a standard Dorrance hook, Fig. 20, was modified to include center control and two links, one of which was pivoted to the fixed finger and the other to the movable finger. Both links were pivoted to a cable which passed through the center of the hook attachment. As can be seen from the illustration, a pull on the cable caused the ends of the links to move apart, thus separating the fixed and movable fingers. The principal advantage in this hook is the center control feature which eliminates undesirable eccentric loading of the wrist, usually caused when opening a conventional hook. Although a six pound force on the cable resulted in a grip of only three pounds force, this hook did not exert sufficient grip pressure to handle easily such a commonplace article as a water glass. Changes in the length of the links, however, make it possible to change the opening forces slightly.

The experience gained with the previous hooks pointed clearly to the need for an entirely new approach to hook design. Toward that end a pull-to-close hook, Fig. 21, was designed with a force multiplier, a lock, a center control, and a wrist disconnect. The movable finger normally was lightly spring loaded to remain open. A pull on the control cable operated against the opening spring and pulled the movable finger closed upon an object or the fixed finger. If any resistance was met in closing, the force multiplier was put into action, increasing the force of the grip 2.4 times to 1, and at the same time, a locking pawl moved into a ratchet locking the fingers at the desired gripping force. This allowed the cable to be relaxed while the grip still was maintained on the object. At a second pull upon the cable, the locking pawl and force multiplier were disconnected from the movable finger which then opened under the force of the opening spring allowing the object to be released. Thus, a variable gripping force was available ranging from that allowed to pick up a marshmallow to that of securely handling a cradle-type telephone. Demonstrations have shown the practicability of this pull-to-close hook, and a redesign of the force multiplier and opening spring should improve the action of this hook even more.

(4) ***Artificial Leg Design.*** *(a) Suction Sockets.* Of the three basic methods of attachment of artificial legs, the shoulder suspension, the belt or pelvic suspension, and the suction socket, work at Northrop was concentrated on the suction socket because of the amputees preference for a minimum amount of harness. Study of the German method of manufacturing suction sockets led to the development of a new design consisting of a single shell socket, the end of which was fitted for connection to the knee mechanism and which had a valve near the bottom of the socket, set on the inside of the leg. This suction socket was laminated from low-pressure phenolic plastics and was formed over a plaster mold. Layers were built up to the desired thickness and when completed the plastic was smooth and could be cleaned easily with soap and water. Flexibility of such a socket is a safety feature in that it can absorb hard knocks without breaking or being permanently distorted.

The chief advantages of this design of a suction socket are the new bearing and relief points on the rim. While some of the old types of German suction sockets tended to cut off circulation and cause sore points on the stump, this redesign has practically eliminated this trouble.

A problem attendant on the design of the suction socket was the construction of a satisfactory valve which would maintain the correct negative pressure (vacuum) during the walking cycle. The construction and testing of several types of valves led to the final acceptance of a valve, Fig. 22, which incorporated the best features of other valves tried and was completely satisfactory in service. Construction is of the flapper, poppet type, and sealing under low pressure proved excellent, while positive pressure of low magnitude opened the valve.

(b) Anatomical Leg. It has been known for a long time that the path followed by the bones at the knee joint is not a simple pivotal motion, but instead is a curve dictated by the shape of the mating bones, the center of rotation of which moves aft as the knee is flexed. The purpose of designing an anatomical leg was to determine the advantages and disadvantages of a normal knee compared with the single pivot type. An X-ray study of the normal knee in various degrees of flexion furnished data on the nature of the movements and from these a proper linkage was designed to obtain a similar motion. In Fig. 23, this anatomical knee mechanism is illustrated. Cams operated by the relative position of the foot and ankle, and by the toe and foot, actuate a push-rod which passes through the center of the pylon to a snubber valve linkage, which in turn, closes the valve against a small spring. A hydraulic

Fig. 21. Pull-to-close hook with force multiplier and locking mechanism.

Fig. 22. Suction socket valve.

Fig. 23. Anatomical knee mechanism.

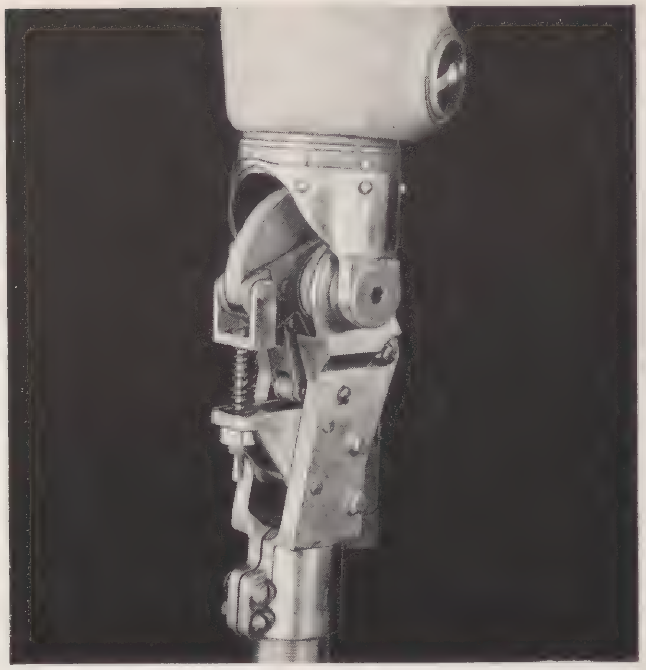


Fig. 24. Hydraulically acutated mechanical knee lock.

vane type snubber is used rather than a positive lock and a valve in the vane permits free flow of the liquid around the vane allowing the knee to flex freely. Links of this knee are spaced across the width of the knee so that the leg is stable under side loads. It has been considered that a below-knee amputee, who needs a rigid knee joint, can use this type of joint since it follows the same motion pattern as the natural knee.

(c) Hydraulically Actuated Knee Lock. The hydraulic knee lock actuator, shown in Fig. 24, used two metal bellows connected by aluminum tubing and filled with hydraulic fluid, thus making a closed system, eliminating the probability of leakage. Compression of the bellows in the foot caused extension of the knee bellows which in turn, actuated the self-energizing type mechanical knee lock. Cams in the foot operated the bellows as the angle between the foot and leg changed. It was discovered that the positive knee lock, while giving satisfactory service during the ordinary walking cycle, was too abrupt and harsh in action when used in cushioning the shock of a fall, and that a redesign must be necessary to allow a more desirable slowing down mechanism to ease the knee to the ground. At present this positive lock and the hydraulic actuating mechanism for it have been abandoned in favor of a more promising type.

(d) Mechanically Actuated Knee Snubber. This knee was designed to test the vane type snubber as opposed to the positive brake. It consisted of a single pivot knee mechanism with a vane type hydraulic knee snubber and lock. A push-rod running through the shank operated the valve of the snubber through a mechanical linkage. The push-rod was controlled by two cams installed at the ankle joint, one of which was fastened rigidly to the foot and the other operated by a push-rod from the toe. This valve did not lock the knee, but gave a slow, controlled rotation which had little time to act during the ordinary walking cycle but softened the roughness and snap of the positive lock and cushioned the fall. This leg has not been tested completely so no final evaluation is available.

(e) Mechanical Knee Lock. Another design which attempted to solve the problem of the knee lock is illustrated in Fig. 25, showing this single pivot type knee with bushings. It has a positive clamping, self-energizing brake and an adjustable friction type drag which prevents over-control when the leg is swinging forward. A push-rod, operated by the position of the foot, automatically locks and unlocks the knee at the proper points in the walking cycle. The shank is a tubular pylon riveted to the ankle bracket and threaded into the knee bracket for adjustment. The foot is pivoted at the ankle bracket which has rubber bumpers to limit foot movement and to cushion shocks. While the original design of this leg was simple, noise of operation, an over-sensitive lock,

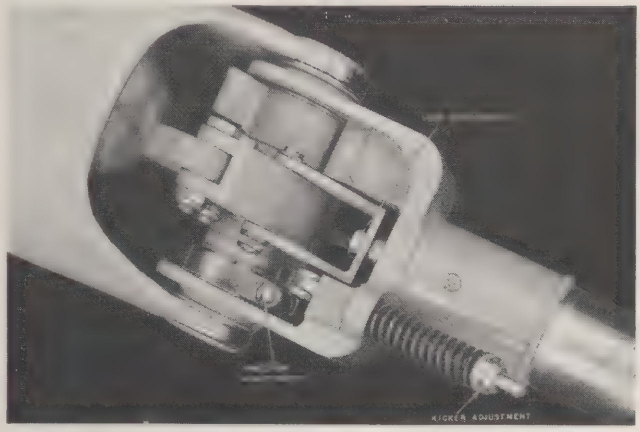


Fig. 25. Mechanical knee lock.

and methods of lock control have proved to be major drawbacks.

(5) Gait Studies by X-ray Cinefluorography. When the Committee with its various subcontractors began research on lower extremity prostheses in June, 1945, it became evident quickly that few data were available on human gait analysis. As a result, Northrop Aircraft was requested to participate in this investigation by constructing a dynamic force plate (described below) to measure the foot reactions and also to develop a method of taking and analyzing high-speed X-ray motion pictures. This program, then, was to obtain and correlate these records of foot reactions and high-speed X-ray photographs of the ankle joint and the knee joint in an analysis of the mechanics involved in walking. In Fig. 26, one can see the X-ray tube, fluorescent screen, and the attendant optical system mounted on a carriage which rides on rails on either side of the ramp. The carriage is driven along the rails by an electric motor and through a rather intricate arrangement follows the subject as he walks down the ramp and carefully centers the X-ray photographs about the subject's knee.

A series of records were taken for subjects during level walking, ascending and descending stairs, and ascending and descending inclines. From these records the following data were available for analysis: (a) X-ray motion pictures of the knee joint and the ankle joint, (b) oscillograph tapes of reactions on the force plate, and (c) external motion pictures of the subject positioned by the screen grid. While no attempt has been made to draw any conclusions from the available data, the equipment as constructed seems adequate to complete this program, and through it an accurate and statistical survey of the dynamics and kinematics of human gait will be made.

Fig. 26. High-speed X-ray photographic equipment.

(6) Plastics, Plaster, and Cosmetic Coverings. *(a) Plastics.* For a period of over two years Northrop Aircraft, Incorporated has been engaged actively in the development and manufacture of limb prostheses from low-pressure laminated plastics. The latter part of this activity has been devoted to experimentation to improve basic techniques, tooling, and the compounding of suitable resinous materials.

Before deciding in favor of the low-pressure laminates, a survey was made of all the materials normally employed in conventional limb prostheses. Various kinds of wood, leather, magnesium alloys, aluminum alloys, stainless, high carbon and other alloyed steels, all were evaluated with respect to weight, strength, workability, serviceability, and sanitation. Of the low-pressure plastics, both the thermoplastic and thermosetting family of resins were investigated for use in limb prostheses. The thermoplastic resins were eliminated from the final selection because of their low strength-weight ratio, poor dimensional stability, and ease of delamination under stress. Compared with all other materials, the thermosetting resin low-pressure laminates were found to be handled most easily in the shop and fabrication techniques were acquired easily by skilled laborers. For arm prostheses, cotton or nylon stockinette for laminating material were found to be adequate in strength and considerably lighter in weight than any other standard commercial arm material.

Fig. 28. Forearm section showing a polyvinyl alcohol bag being stretched over a completed lay-up.

Fig. 27. Forearm section showing plaster tooling, metal inserts and stockinettz lay-up.

In Fig. 27, a step of arm manufacture is illustrated by the positive plaster cast of a forearm section with metal inserts and stockinette positioned on the cast. Finished forearm sections are stacked in the background. In the next step, a protective polyvinyl alcohol bag, Fig. 28, is stretched over the completed lay-up and subsequently the resin is poured into the small end of this covering and forced down and into the fabric lay-up. Air bubbles are removed and in Fig. 29, the assembled parts are placed in an oven for curing.

After the cured laminated structure has been cooled thoroughly, the plaster is broken out by striking a rubber mallet against the arm shell, and the arm is trimmed and sanded. It then is dried in an oven and the low-pressure laminated outer shell

Fig. 29. Forearm and upper-cuff sections in curing oven.

component is ready for assembly of the wrist mechanism to the outer wrist housing.

As more information becomes available on the use of plastic laminates this development continues, but it seems reasonable to assume that a major change will come only as the result of the introduction of new materials into the field of plastics.

(b) Cosmetic Coverings. A study of the requirements for a successful covering for artificial limbs pointed to the difficulty of finding a single material which would fulfill all of the functions desired. It was decided that the best course lay in the simultaneous use of two materials: an inner filler which would hold the shape and general contours of the hand, arm, or leg, and an outer covering which would be resistant to solvents, tearing, could be cleaned easily, and would contain the lines, veins, and fingernails simulating those existent in a natural member. Many materials were investigated for the inner covering and for the outer covering, but none of the materials was completely successful. The process for coloring and making the hand look natural also was studied, but here again, it was not completely successful.

(7) Limb Fitting Technique. The fitting and aligning fixture shown in Fig. 30, was designed at Northrop for measuring certain characteristics of the human skeletal structure in the hopes of eliminating some of the mistakes in ordinary limb fitting methods. It consists essentially of three vertical pillars of aluminum tubing mounted on a baseboard with the upper ends of the tubes supporting a semicircular section to act as an arm support. The two lateral tubes have steel measuring tapes riveted to them so that the height of various attachments can be measured directly from the base. The leveling attachment, Fig. 31, is used to subject the amputee to erect posture, and attachments for measuring the crotch height and the knee axis also are available. For use on subjects where suction sockets are not practicable, it becomes necessary to use some form of pelvic band suspension, and it is necessary to locate the axis of the hip in space. For accomplishing this function a hip axis attachment is available on the fitting fixture.

Fig. 30. Northrop fitting and aligning fixture.

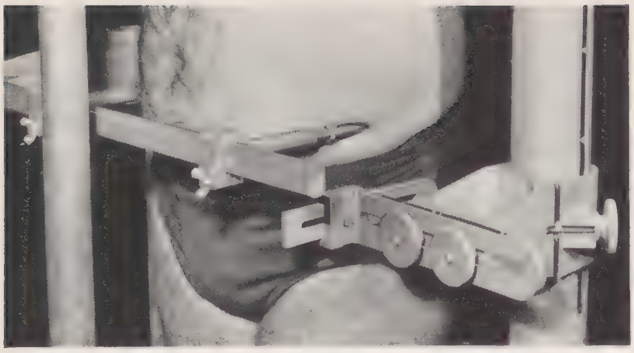


Fig. 31. Leveling attachment on fitting fixture.

(8) Harness Study. Only by the study of the problems of the amputee can one realize the tremendous task that is yet to be achieved in the design of suitable systems for harnessing muscular movements for the operations of upper extremity prosthetic devices. From extensive study of harnesses by this group, an insight into the psychological reactions of the amputee has led to the limiting of the number of voluntary controls available to three: (a) actuation of a control by the fore and aft motion of the upper arm stump, (b) actuation of a control by the downward shrug of the shoulder on the side of the amputation, and (c) actuation of a control by the forward shrug of the shoulder on the side opposite the amputation. A comprehensive report analyzing harnesses of different types made for various amputees at Northrop Aircraft has been compiled. One of the twenty-three various types of harnesses, which is shown in Fig. 32, is the standard arrangement of harness for the bilateral below-elbow amputee. This type has been employed successfully on a number of unilateral and bilateral below-elbow amputees.

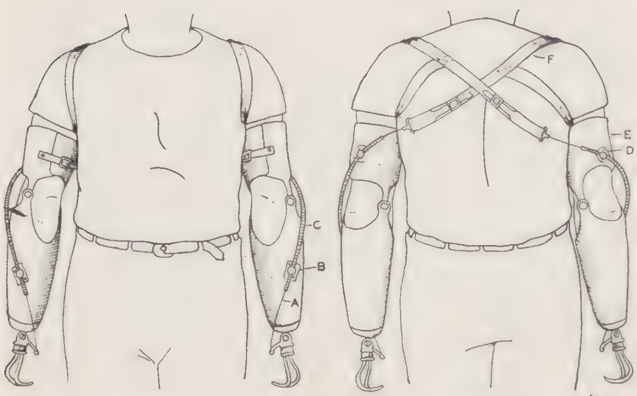


Fig. 32. Harness used on below-elbow bilateral amputees.

Fig. 33. Northrop force plate.

(9) Force Plate. To assist in the dynamic analysis of human locomotion a force plate, Fig. 33, was developed which was designed to measure the magnitude, direction, and point of application of each force exerted by the foot. Forces measured were vertical load, side load, fore and aft loads, and the couple or torque load.

The force plate is primarily a magnesium structure eighteen inches long, the upper plate of which is designed to be recessed in the floor with the top surface flush so that a subject could step on the plate at his normal gait. This upper plate is movable and as the subject steps on this plate, forces are recorded continuously by a recording oscillograph. These data are recorded simultaneously with X-ray photographs and external motion pictures as described above. The force plate has contributed a great deal to the problem of analyzing each limb of the lower extremity as a free body for use in the design of a more functional artificial leg.

GOODYEAR TIRE & RUBBER COMPANY

Akron, Ohio

BACKGROUND. Through the interest and guidance of Dr. Harold R. Conn, Medical Director of the Goodyear Tire & Rubber Company Employees' Hospital and a Member of the Committee on Artificial Limbs, a contract was negotiated in October, 1945, to conduct studies and experimental investigations toward the development of a light metal artificial foot making use of bonded rubber inserts for the ankle joint. It was suggested by the Committee that the ankle joint should provide for a limited amount of lateral flexion in addition to the usual plantar and dorsal flexion. The work was under the supervision of Mr. H. E. Morse, in charge of mechanical goods, with Mr. R. E. DePuy and Mr. E. M. Burger as project engineers. Mr. C. S. Davis, Administrative Assistant of the Government Sales Department, also was helpful to the project. The experience of Goodyear in the fabrication of parts involving the bonding of rubber to metal plus their facilities of an experimental job shop and a dynamic testing laboratory made it a potential asset to the overall program in the development of artificial limbs.

PROJECT. As the first step toward an improved design, a study of the structure and function of the human foot and ankle was undertaken. Various commercial feet and ankles were measured and analyzed and as a basis for preliminary design and a plaster cast of a normal human foot was measured and studied.

The essential component of the ankle joint developed by Goodyear was a biaxial torsion unit consisting of two mutually perpendicular cylinders, each containing a concentric shaft with a layer of rubber securely bonded between the shaft and the outer cylinder. Flexure of the ankle in either plane introduces a torsional shear in the rubber element of the corresponding axis. The degree of rigidity is a function of the dimensions of the torsion resisting element and the physical properties of the rubber. If the final design is commercially produced, the tubular elements will be available in various combinations of stiffness about each axis. In Fig. 34, the basic structure of the foot and ankle design is shown.

The final assembly of the Goodyear artificial foot was comprised of seven essential parts: the foot structure, the ankle block, the ankle toggle, the toe structure, the bumpers, the cosmetic filler, and the latex cover. A side view of the finished working model is shown in Fig. 35, without the filler and cover. The

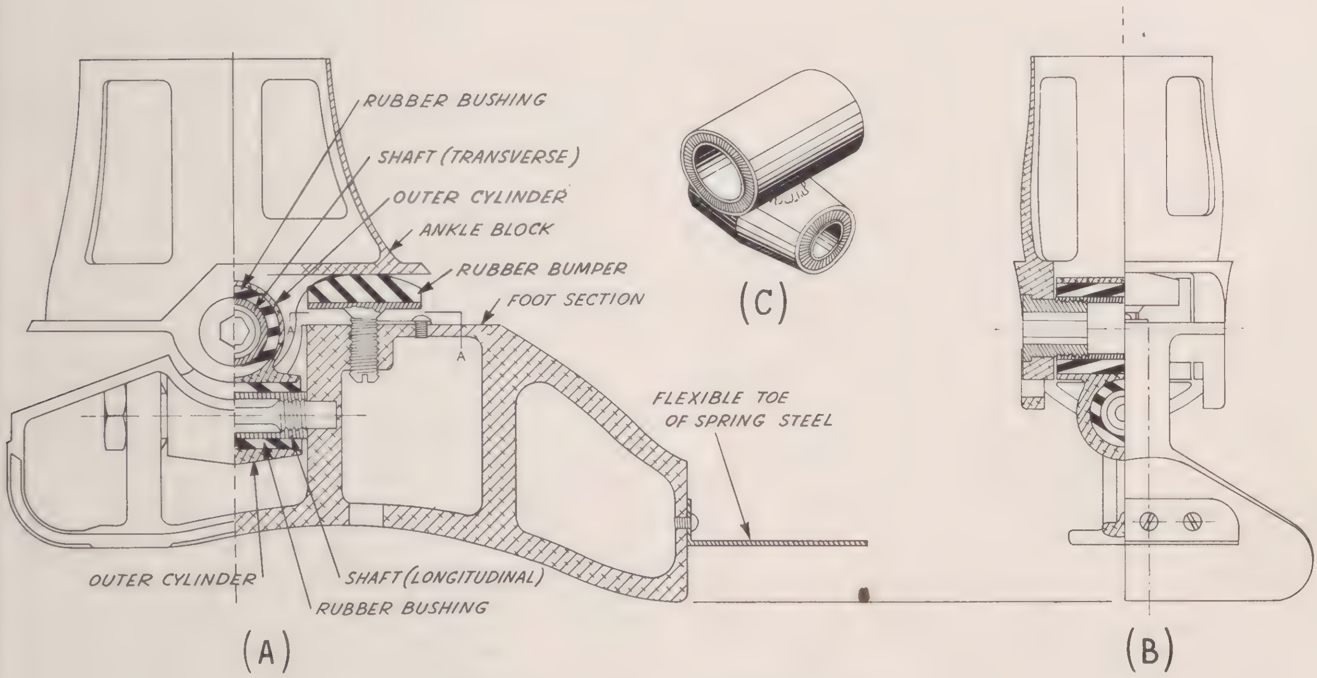


Fig. 34. Foot and ankle basic structure.

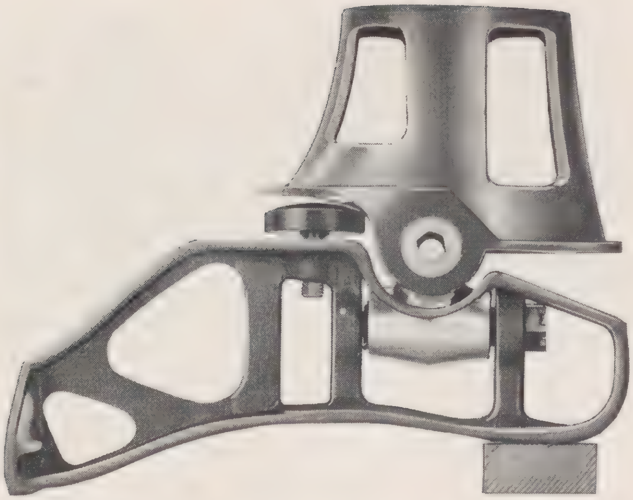


Fig. 35. Side view of working foot model.

foot structure and ankle block were cast out of aluminum and the ankle toggle was designed to be forged of steel and machined to allow for the insertion and bonding of the rubber fillers. The bumper is adjustable thus permitting shifting of the angle of the shin with respect to the foot, and was fashioned of hard rubber and attached to a metal pedestal threaded into the foot section. Filler material was air foam, a cured, whipped latex, and a cosmetic covering of gum latex was deposited on a metal form by means of an electrolytic process and allowed to cure. The total weight of the working model was 694 grams (approximately one and one-half pounds), and a further reduction in weight may be expected by the substitution of lighter metals.

Although work was halted on this project in December, 1946, before all final tests had been made thus eliminating the possibility of securing a conclusively improved final design from this subcontractor, there is indication that a foot of this type may become a worthy addition to the field of artificial limbs.

RESEARCH INSTITUTE FOUNDATION

Detroit, Michigan

BACKGROUND. In 1943, the Orthopedic Appliance and Limb Manufacturers Association (then the Association of Limb Manufacturers of America) established a nonprofit organization for the purpose of conducting research and development projects relating to the artificial limb industry. Members of the Committee on Artificial Limbs thought that it would be profitable to its program to establish contact with the limb manufacturers through this Foundation and thereby draw upon the practical knowledge of limb manufacture and fitting that resides in this industry. In August, 1945, the Research Institute Foundation was invited to participate in a research program to investigate methods for fabricating sockets of plastic materials for amputations involving hip and shoulder disårticulations, and to develop practical knee and elbow locks for use in disarticulation cases.

The projects in this subcontract were placed under the direction of Mr. F. O. Peterson, treasurer of the Foundation and expert limb fitter, who was assisted by Mr. A. M. Reynolds, plastics engineer, and Mr. Harold Smith, mechanical engineer.

PROJECTS. ***(1) Disarticulation Sockets.*** The first problem was the development of a simple method of forming the socket. A bag-molding technique was used first in which the laminated plastic was placed over a positive plaster cast of the stump, covered over by a closely fitting rubber bag from which the air was exhausted, and cured in a baking oven at the correct temperature for the proper length of time. In Fig. 36, the steps which were followed in bag-molding a disarticulation socket are illustrated: (a) a negative plaster cast of the stump was made; (b) a positive plaster replica then was formed from the negative; (c) a rubber bag was made by dipping the positive plaster cast several times in rubber latex and curing the resultant replica in a hot air oven; (d) a laminated plaster socket then was formed over the positive plaster cast and inclosed by the rubber bag.

It was found later that replacement of the rubber bag described above by polyvinyl alcohol sheeting constituted a simpler procedure and furnished as satisfactory a resulting product. Various thermosetting resins with suitable catalysts were tried in combination with laminating materials such as knitted cotton stockinette, knitted Celanese tubing, nylon woven fabric, rayon woven fabric, and Fiberglas woven fabric.

Experiments were conducted also upon a blow-molding technique in which a sheet of uniformly heated thermoplastic material, such as Plexiglas, was forced to conform to the shape of the interior of a hollow mold by means of air pressure. This method furnished a smooth, glossy inside surface difficult

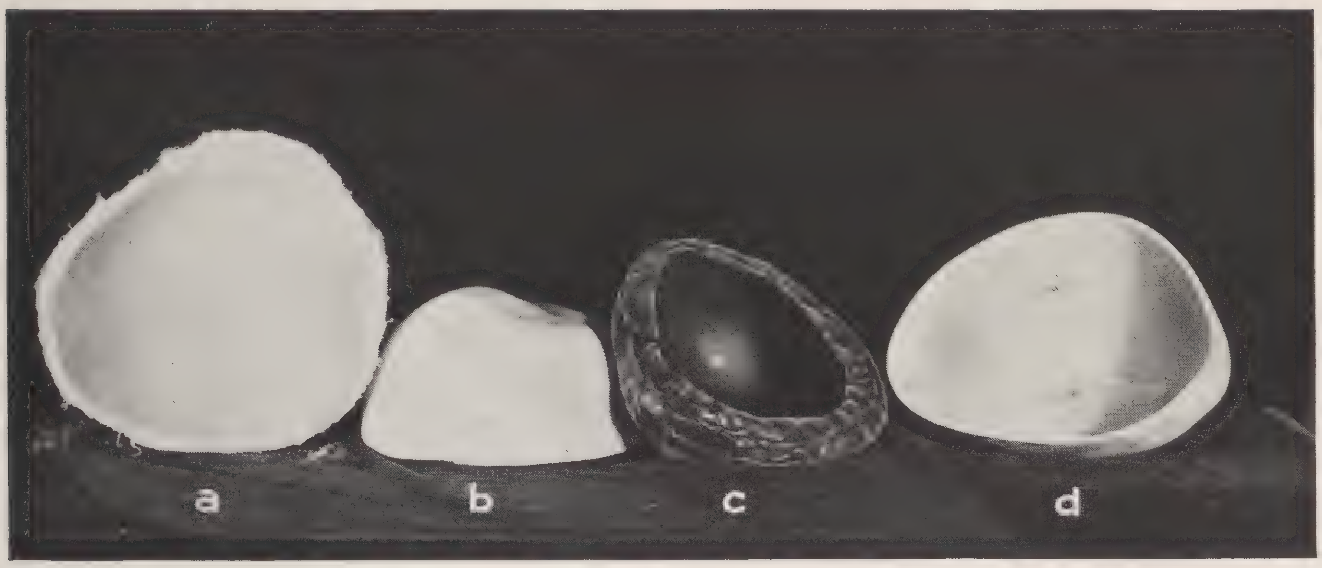


Fig. 36. Steps followed in bag-molding a disarticulation socket.

to obtain with the plastic laminates without careful coating with lacquer. Furthermore, the use of thermoplastic materials indicated an additional advantage of permitting later revision of the socket in altering its shape and dimensions to fit the changing requirements of the amputee.

The plastic socket, made with either laminated thermosetting resins or transparent thermoplastic materials was aligned in the wooden thigh piece and glued in place by a suitable plastic glue. Patients on whom these sockets were tried seemed to get better results than from the conventional tilting-table socket. Plastic sockets were quite comfortable, did not show through the clothing, and could be readily washed with soap and water.

(2) Knee Locks. The development of a satisfactorily controlled knee lock for the amputee with a disarticulated hip should do much to eliminate an unnatural gait. As the first mechanical approach to this problem, a simple brake-band lock, the band of which partially encircled a brake drum at the knee, was attempted. Pressure on the toe forced it up, thus releasing the brake and allowing the knee to flex. A singly wrapped spring lock for the knee which was actuated automatically to prevent flexion of the knee and which unlocked to prevent knee extension also was tried.

A hydraulic piston and cylinder arrangement placed in the shank of the artificial leg was the first attempt by this subcontractor toward the development of a hydraulically controlled knee lock. In Fig. 37, this design is illustrated. Weight on the toe

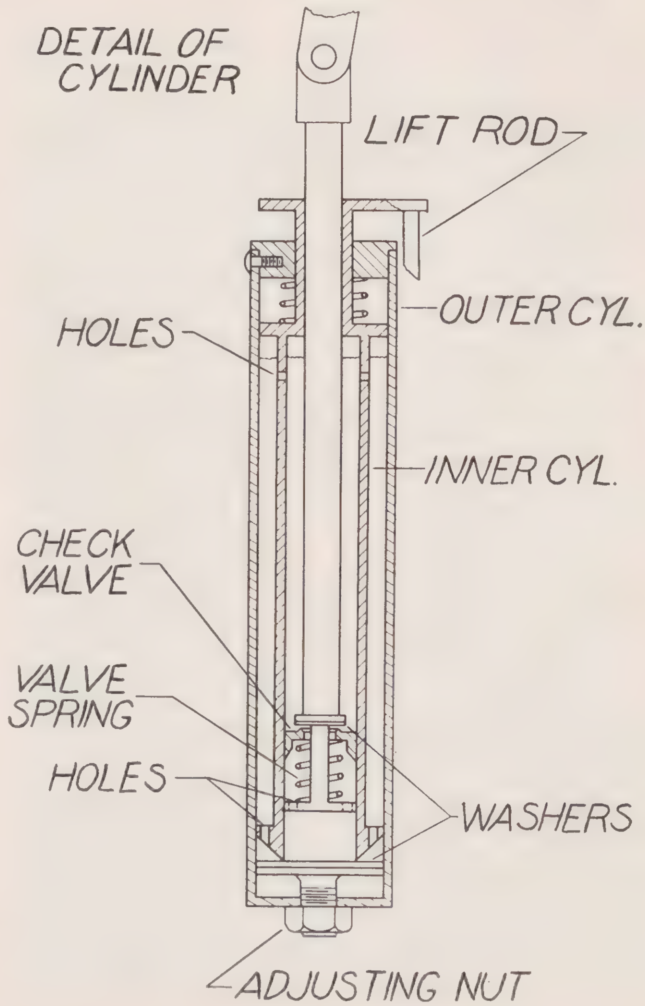


Fig. 37. Hydraulic knee lock.

compresses a hydraulic bulb which in turn lifts the plunger at the ankle, causing the hydraulic cylinder to unlock. Weight on the heel allows the lock to remain engaged.

(3) Elbow Locks. A singly wrapped spring elbow lock was designed and constructed which, in limited tests, seemed to function adequately. A doubly wrapped elbow lock was tried also but further engineering refinement was needed before a reasonable approach to a practical unit could be expected.

UNIVERSITY OF CALIFORNIA

Berkeley, California

BACKGROUND. It became apparent quite early in this program of development of artificial limbs that a great need existed for a background of fundamental information to yield basic data on human locomotion and the mechanics of walking which, in turn, would provide design criteria for an improved artificial leg. The University of California at Berkeley, because of particular cooperation between the Medical and Engineering Schools, seemed to be an eminently suitable contractor to undertake such investigations.

Professor Howard D. Eberhart of the Division of Civil Engineering and ultimately head of this project had acquired a personal interest in the development of improved prostheses since he had become a below-knee amputee as a result of an accident which occurred while engaged in research work for the Army Air Forces at Hamilton Field near San Francisco. Even before this accident, however, Professor Eberhart and Dr. Verne T. Inman, Assistant Clinical Professor of Orthopedic Surgery at the University of California Medical School in San Francisco, had been in consultation on biomechanical problems related to the behavior of the shoulder joint. This cooperation between the School of Engineering and the School of Medicine made this subcontractor additionally valuable to the efforts of the Committee on Artificial Limbs. Among those cooperating directly with the program were Professor A. S. Levens, Department of Mechanical Engineering, who was of general help throughout the project, particularly in connection with the pin rotation studies; Dr. John B. de C. M. Saunders, Professor of Anatomy at the Medical School, who was a consultant in medical matters and assisted in the over-all organization, bibliographical studies, and synthesis of the results on locomotion; Dr. T. C. McCown, Associate Professor of Anthopology, who was in charge of the anthropometric survey and the analysis of the data; and Mr. Don O. Horning, engineer on leave from Consolidated Vultee Aircraft Corporation, San Diego, who was in charge of supervising and coordinating the activities in the Engineering Materials Laboratory.

As a result of meetings entered into by the Members of the Committee on Artificial Limbs with representatives from the College of Engineering and the Medical School of the University of California, a contract was negotiated and work was begun at Berkeley in September, 1945.

PROJECTS. In order to achieve the aims of this research project and to outline the objectives more clearly, the program was divided into two main parts:

(A) A STUDY OF THE FUNDAMENTALS OF THE MECHANICS OF LOCOMOTION,

(B) ENGINEERING AND MISCELLANEOUS PROJECTS.

In the study of the mechanics of locomotion, data relating to the displacement and rotation of the limb in space, ranges of movement, velocities and accelerations, harmonic analysis of limb motions, internal and external forces acting upon the limb, the phase and action of the musculature, and factors contributing to the comfort of the amputee were compiled and analyzed. The first eight subdivisions of the program cited below may be considered under the heading of locomotion. Problems involved in engineering and miscellaneous projects are concerned with the choice of materials used in prostheses, determination of factors involved in alignment criteria, plans in connection with design and structural analysis, and the examination of the engineering possibilities of the utilization of remaining muscles in the amputee to provide motor mechanisms. In general, projects nine through sixteen listed below cover the second phase of this program.

(1) Study of Rotations During Locomotion, Using Pins. The study of the fundamental properties of the mechanics of walking at the University of California has given indications that transverse rotations of the various segments of the leg are an important factor in producing ease and rhythm of walking in normal individuals. Transverse rotations refer to horizontal projections of the angular displacements of the tibia, femur, and pelvis about their

Fig. 38. Dr. Inman threading pins into cortices of bony prominences adjacent to the hip and knee joints.

longitudinal axes. If provision is made in the artificial leg to allow a repetition of these transverse rotations of approximately the same order of magnitude as is present in normal legs, the probability of improved function, reduced fatigue, and prevention of abrasion at critical points of the stump of the amputee, may be enhanced. In trying to determine the magnitudes of transverse rotations of the segments of the lower extremity, it was found unsatisfactory to locate the position of these joints by surface markings because of the relative motion between the skin and the bone during walking. In previous research upon the shoulder joint, Drs. Inman, Saunders, and Abbott, all of the University of California Medical School, had perfected a technique for determining the motions of a bone by means of pins inserted through the flesh into the bone. This technique was employed to determine the angular rotations of the leg segments during walking.

Stainless steel pins 2.5 millimeters in diameter were threaded firmly into the cortices of the various bony prominences adjacent to the hip and knee joints using sterile precautions and local anesthesia. In Fig. 38, Dr. Inman is shown performing this operation. Targets, each consisting of a sphere attached to the end of a light wooden rod, were fastened to the pins. In Fig. 39, pins are shown placed in the iliac crest of the pelvis, in the adductor tubercle of the femur, and in the upper portion of the tibia. The insertion of the middle pin into the inner side of the femur was dictated by the fact that placement from the outer side so restricted movement of the leg that motion at the knee was suppressed.

Photographic records of the movements of the targets were obtained by three 35 mm. motion picture cameras synchronized at forty-eight frames per second and so located to refer the targets to three mutually perpendicular coordinate planes. In this manner, top, front, and side views of the subject were obtained simultaneously. A clock mechanism made it possible to identify related frames, which were studied from large projected images.

Photographs of twenty-six subjects, varying in age from eighteen to forty years, were taken for straight and level walking, up and down a ramp, and up and down stairs. Because of excessive pin vibrations,

Fig. 39. Subject with pins and targets attached.

bending of pins, single pin settings, and mechanical difficulties, data from only twelve of the subjects were considered satisfactory for study and analysis. Complete analyses have been made only of the data dealing with the top view for straight and level walking.

Results of this research have shown that the average magnitude of the rotation of the pelvis during the walking cycle is 8.0 degrees, that of the femur 15.2 degrees, and that of the tibia 19.3 degrees. An average value of 9.1 degrees was determined for the relative transverse rotation of the tibia with respect to the femur, the magnitude and time of occurrence of which is of particular interest because of its relation to the locking mechanism of the knee. When the knee is locked (fully extended), inward rotation of the femur occurs; unlocking the knee results in external rotation. Relative transverse rotation of the femur with respect to the pelvis was found to average approximately 8.2 degrees for the normal subject.

These experiments indicate that internal and external rotations of the various segments of the lower extremity are related to weight-bearing. Internal rotations take place during the phase of no load to full weight-bearing, and external rotation takes place during the phase of full weight-bearing to no load. In Fig. 40, composite curves are shown which indicate the average rotation in degrees of the tibia, femur, and pelvis for all subjects and reveals this finding clearly.

Such transverse rotations as evidenced by this project appear to be absorbed in the articulations of the foot and in its related ligamentous structures. It seems apparent that the development of an artificial foot and ankle should take cognizance of these rotations and their effects upon the structure and functions of the foot.

Findings of this project indicate that a lower extremity prosthesis not incorporating mechanisms providing for transverse rotary motions cannot behave as a normal leg and necessarily requires alterations in the normal pattern of movement of the joints proximal to the amputation.

(2) Ankle Rotation Studies. In the above report covering transverse rotations of the pelvis, femur, and tibia, it was concluded that the hip and knee joints permit axial rotations during walking. From these studies the tibia has been shown to rotate during that period of a walking cycle when the foot is firmly planted on the floor, indicating that some horizontal angular displacement must exist between the tibia and the foot during the walking cycle. This conclusion led to studies of ankle rotation.

The studies of ankle rotation were approached in three ways:

(a) Anatomical studies of cadaver joints,

(b) Construction of a shank rotating attachment for artificial legs,

(c) Functional studies of living subjects.

By the use of cadaver ankle joints it was found possible to determine the anatomical limits of horizontal rotatory movements by the pin technique described above. Twenty-one cadaver ankles were partially dissected removing all muscle and tendon structures above the ankle joint. It was possible to fix the foot and control mechanically the axial rotation of the tibia in the normal position, plantar flexed position, and dorsiflexed position, and by means of a steel pin threaded into the tibia horizontal angular

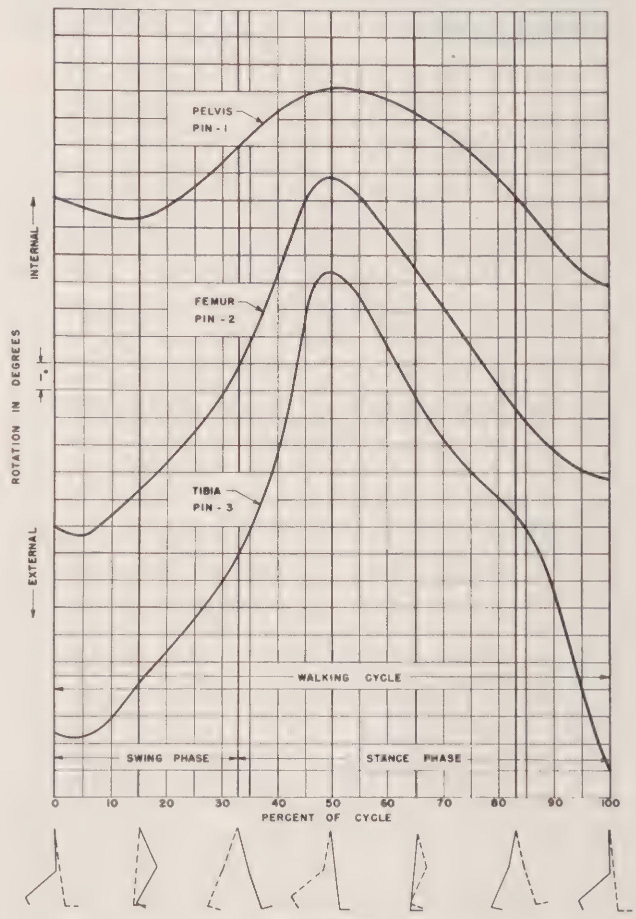


Fig. 40. Composite curves for all subjects showing average rotations in degrees of the tibia, femur, and pelvis at various leg positions.

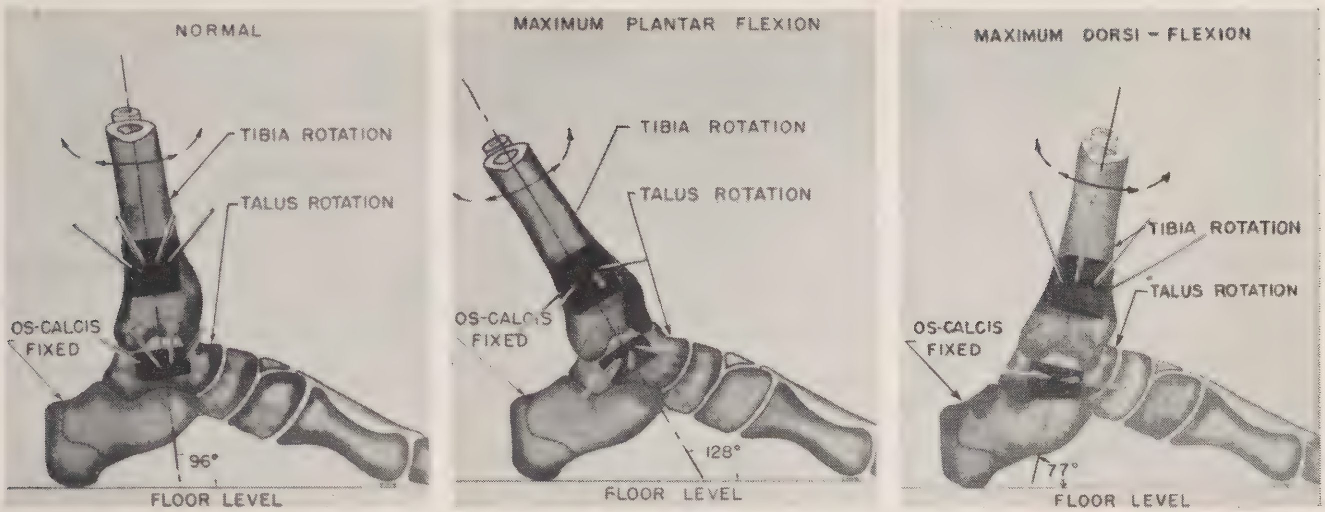


FIG. 41. SUMMARY OF ANKLE ROTATION DATA.

NORMAL POSITION—21 Subjects

Tibial Horizontal Rotation			
Maximum	55.5°	Average	35.5°
Minimum	20.0°	Std. Deviation	9.38°
Talus Horizontal Rotation			
Maximum	42.0°	Average	21.6°
Minimum	12.0°	Std. Deviation	6.87°

% of Rotation in Sub-Talar Joint 60.8
% of Rotation in Tibio-Talar Joint 39.2

PLANTAR-FLEXION—20 Subjects

Tibial Horizontal Rotation			
Maximum	30.5°	Average	23.6°
Minimum	13.0°	Std. Deviation	4.43°
Talus Horizontal Rotation			
Maximum	24.0°	Average	11.5°
Minimum	5.0°	Std. Deviation	3.94°

% of Rotation in Sub-Talar Joint 48.7
% of Rotation in Tibio-Talar Joint 51.3

DORSI-FLEXION—20 Subjects

Tibial Horizontal Rotation			
Maximum	48.5°	Average	32.9°
Minimum	25.0°	Std. Deviation	6.03°
Talus Horizontal Rotation			
Maximum	34.3°	Average	23.0°
Minimum	13.5°	Std. Deviation	4.66°

% of Rotation in Sub-Talar Joint 70.0
% of Rotation in Tibio-Talar Joint 30.0

deflexions were obtained by projection upon recording paper. Angular deflexions of the talus were recorded simultaneously using the same technique. Summarized data appear in Fig. 41 for all twenty-one ankles.

In the normal subject, angular deflections of the ankle joint occur during weight-bearing. Since there was no control of axial load in these experiments, it was recognized that conditions of this cadaver joint study do not duplicate exactly those found in the living subject. Enough quantitative information was collected, however, to permit the design of an experimental shank rotatory device for artificial legs. This adjustable mechanism, which permitted relative horizontal rotation between the upper and lower parts of the artificial shank, was constructed. In Fig. 42, this ankle rotation pylon is shown. Two horizontal bearings located at the bottom of the aluminum pylon allow rotation of the ankle fixture which is attached to the foot. Rigidly attached to the ankle fixture and the pylon is a torsion rod which returns the foot to a normal fore and aft position when in the swing phase. Rising from the ankle fixture is an adjustable bumper which strikes the stops attached to the pylon. The desired inward and outward angle of rotation can be adjusted from zero to twenty degrees. The torsional constant of the spring rod is two inch-pounds per degree, which low value prevents "whip" of the prosthesis when the foot is returned to the neutral position.

The first above-knee amputee to use this shank rotary device, enthusiastically reported immediate

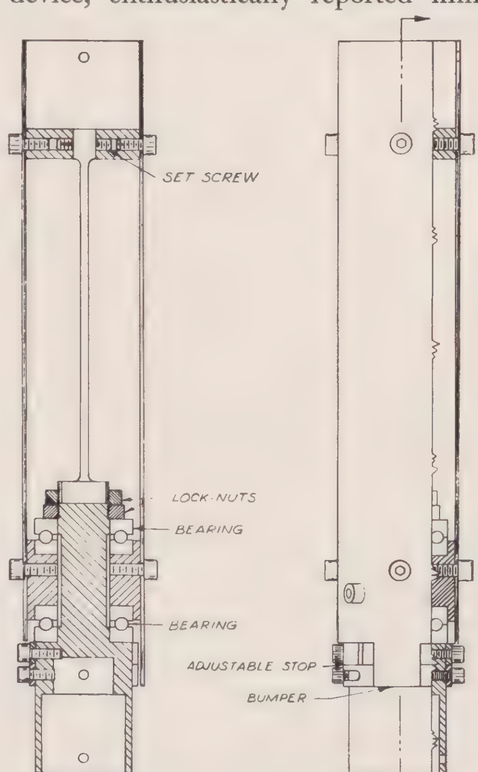


Fig. 42. Ankle rotation pylon.

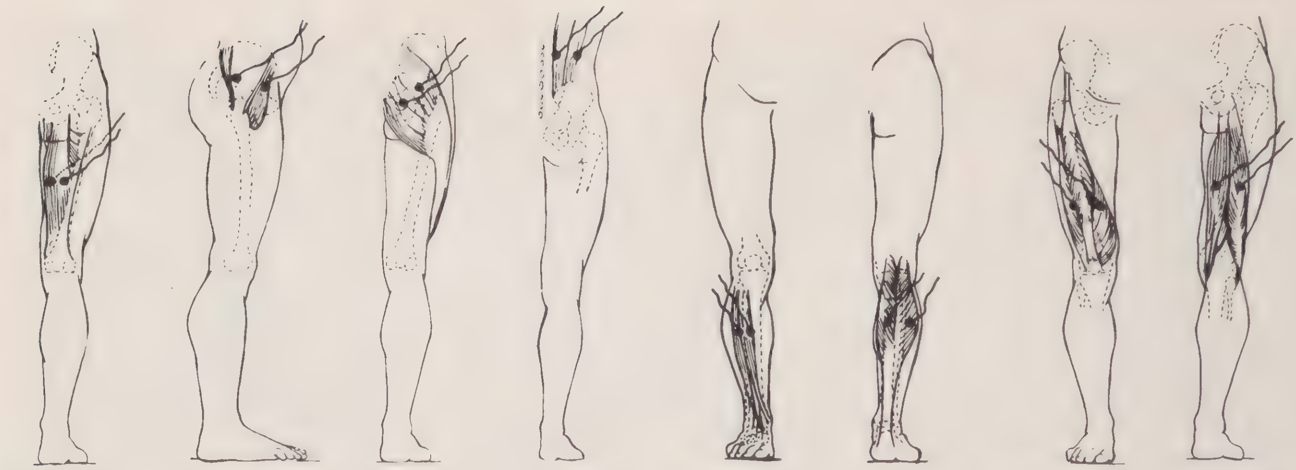


Fig. 43. Study of muscle groups showing electrode positions.

improvement and comfort due to marked reduction of irritation and pain at the ischial seat. Increased comfort and freedom of action has been confirmed so far by three above-knee amputees and one below-knee amputee. Some improvement in gait was observed, and a new feeling of stability was reported; longer and more natural strides seemed evident.

While the original pin studies of the normal leg gave the range of horizontal angular displacements which occurred at the knee joint during walking, rotations between the foot and tibia were not measured because of the inadvisability of placing pins into the smaller bones of the foot in the living subject. It was later found that such data were procurable by the use of the glass walkway (described in Project 5) in conjunction with a single tibial pin. Angular displacements between the pin target and the marked shoe sole in the horizontal plane for both stance and swing phase were obtained from motion picture records. These data confirmed previous findings and gave an indication of the ranges of relative rotation at the ankle joint.

(3) Pattern of Muscle Activity in the Lower Extremity. While the construction of an artificial leg designed to simulate the action of the normal leg is a prime consideration, the behavior of this prosthesis is dependent also upon the skill and facility with which forces generated in the muscles of the stump are transmitted to the appliance. For this reason a study of major muscle group patterns of control was considered to be an important phase in the program of collecting fundamental data on the mechanics of walking.

It long has been known that muscular contraction is accompanied by minute changes in the electrical potential of each of the many fibers which constitute the muscle mass. By means of an electromyograph, these muscle potentials can be amplified, recorded, and analyzed to reveal action patterns from the major muscle groups of normal subjects during various walking activities. While actual quantitative measurements of force were not established by this method because of a nonlinear and, as yet, undetermined relationship between muscular and electrical activity, it was possible to record the exact phase of action of the various muscle groups defining the onset and termination of activity as well as the exact period of maximum action. In Fig. 43, the muscle groups studied and the electrode positions used in each are shown. Electromyographic traces were taken on ten normal male subjects, each trace of the myograph then was integrated into an envelope and these curves were superimposed on each other. From these superimposed envelopes evolved the idealized summary curves. In Fig. 44 these curves are shown. The vertical axis on these graphs indicates the order of magnitude of the electrical potential and hence relative muscular action developed during various phases of the walking cycle. From this study a more complete understanding of human locomotion provides a firmer basis for the evaluation of the mechanical behavior of the stump of the amputee. Results also suggest surgical procedures for the improve-

ment in function of the lower extremity amputation stump as it is evident that preservation of certain critical muscle actions would result in functional improvement of the prosthesis.

Data available from this phase of the program have enabled artificial limb designers to simulate normal movement in an artificial leg more accurately by utilizing the force of the stump muscles to actuate control mechanisms. Through knowledge of the activity of leg muscles at each instant during the walking cycle, more precise timing of control systems in the artificial limb should become feasible.

(4) Locomotion Study Using Interrupted Lights. During the early stages of development of this program, the need was realized for some simple and straightforward means of quantitatively determining the normal or average gait for a number of subjects and the individual deviations from the average. One method successfully used was the determination of displacement patterns of the joints in the legs at any instant in the vertical plane of progression by the interrupted light technique.

In this method the subject walked in front of the open lens of a camera while wearing a small light bulb over each center of rotation of the joints of his leg. The bulbs were positioned at the iliac crest, the greater trochanter, the centers of rotation of the knee and the ankle, and the heel and the toe of the shoe. The field of view of the camera was interrupted at short time intervals so that the displacement patterns on the film of the camera appeared to be small lights moving along the path of each joint and flashing at short, equal time intervals. These displacement-time data furnished the necessary relationship for computing velocities and accelerations of any point on the leg. In Fig. 45, such a photograph is illustrated. A Kodatron speed lamp, producing a very high intensity flash with a duration of only 1/25,000 of a second, was used for securing an exposure of the subject at mid-field for purposes of identification.

From these data criteria for partially defining the gait of an average subject were found, comparisons between the gait of the amputees and normal sub-

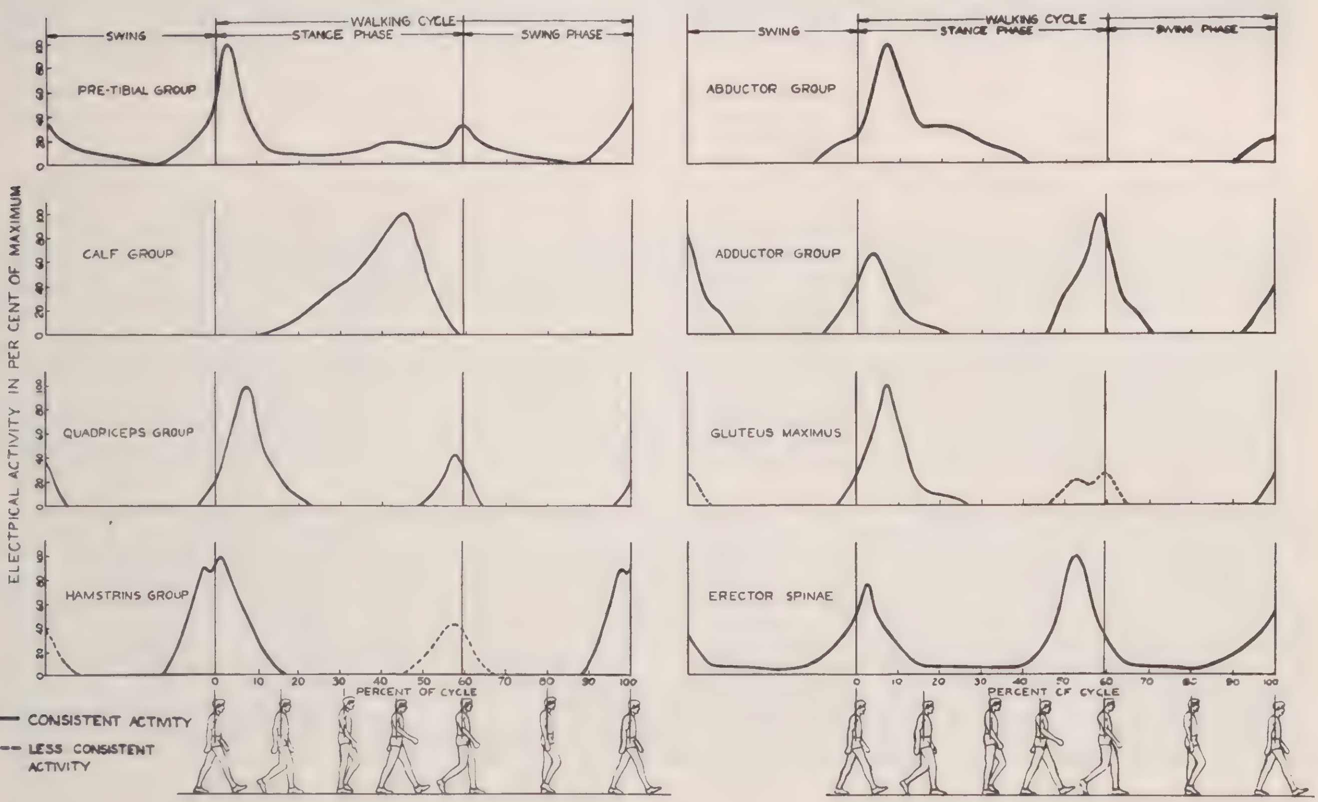


Fig. 44. Idealized summary curves representing major muscle groups during level walking.

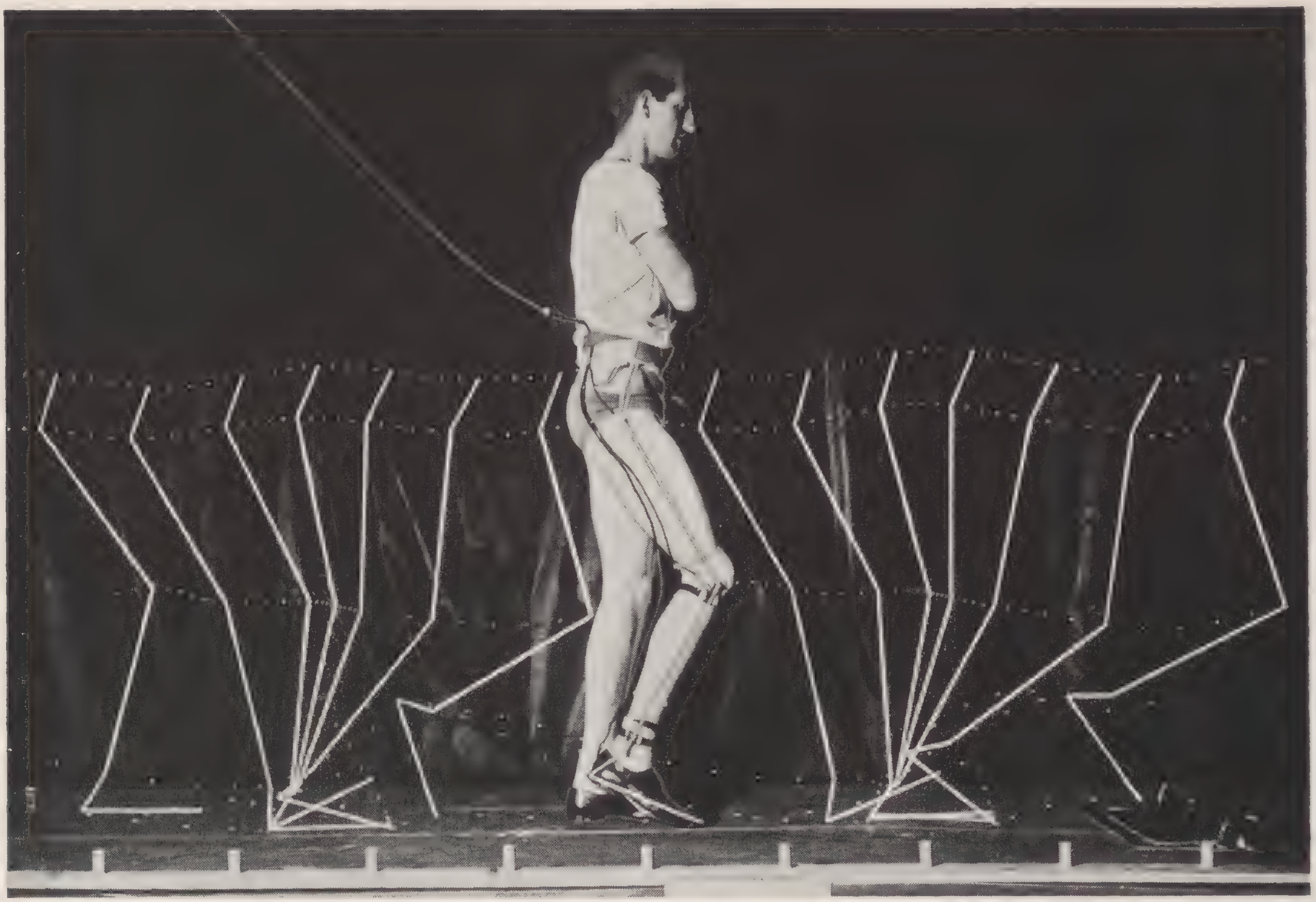


Fig. 45. Normal subject walking showing lines drawn through corresponding positions.

jects were made, and the muscle torque about the knee was calculated. It was realized that a normal subject has a longer stride than a below-knee amputee, and for normals and amputees the longer the stride, the greater the vertical displacement of the trochanter. Muscle moments about the knee were found to be in phase with the action potentials of the extensor and flexor muscles.

A method of correlating various physical quantities involved in human locomotion, such as weight of the subject, speed of walking, muscle action, and forces in the leg using a harmonic analysis of experimental data was attempted. The amplitudes of the harmonic terms obtained show definite correlation with speed of walking and the type of amputation. While the small amount of data analyzed does not seem to warrant any final conclusions, future investigation may disclose possibilities of definite correlation of various factors influencing human locomotion by means of harmonic analysis.

(5) Glass Walkway. During the studies of angular rotations of the lower extremities, it became apparent that additional information was desired regarding relative motions between the leg segments and the foot, as well as the movement of the foot itself. It seemed advisable to study simultaneously the action of the leg and foot as viewed from below and from the side in both the swing and stance phase of the walking cycle. For this purpose a glass platform, one inch thick, upon which the subjects could walk and which would permit photographing from below was built and preliminary tests were run. Provision was made in the design of the glass walkway to include the use of a method devised by Dr. Elftman for the study of pressure distribution between the foot and the floor.

The glass walkway studies brought out the importance of pelvic movement in locomotion. A special frame was constructed and attached to the subject in order to obtain measurements of tilt, twist, lateral

and vertical displacement of the pelvis. It was observed that the displacements of the pelvis of a normal subject are quite symmetrical while the amputees walk with irregular and unsymmetrical displacements of the pelvis. The characteristics of pelvic displacement were used as part of the criteria for functional evaluation of various artificial legs.

Two views of a subject are shown in Fig. 46, on the glass walkway.

(6) High-speed Motion Pictures. Experience in this project had shown previously that actions of the leg in normal walking are not easily detected without the use of high-speed motion pictures. A type III Eastman high-speed camera was made available through the courtesy of the Consolidated Vultee Aircraft Corporation. It is a sixteen millimeter camera having film speeds of 500 to 3,000 frames per second. The film is in continuous motion, the image being moved synchronously with the film by a flat optical glass shutter.

The walking action of twenty subjects has been photographed with this high-speed motion picture camera, four having been normal subjects and sixteen amputees. Inspection of these films has revealed clearly the double locking action of the knee joint of the normal subject. A composite photograph of selected single frame pictures is shown in Fig. 47, illustrating the progressive stages of the double lock of the knee joint of three normal subjects. It can be

Fig. 46. Subject ready for test on glass walkway.

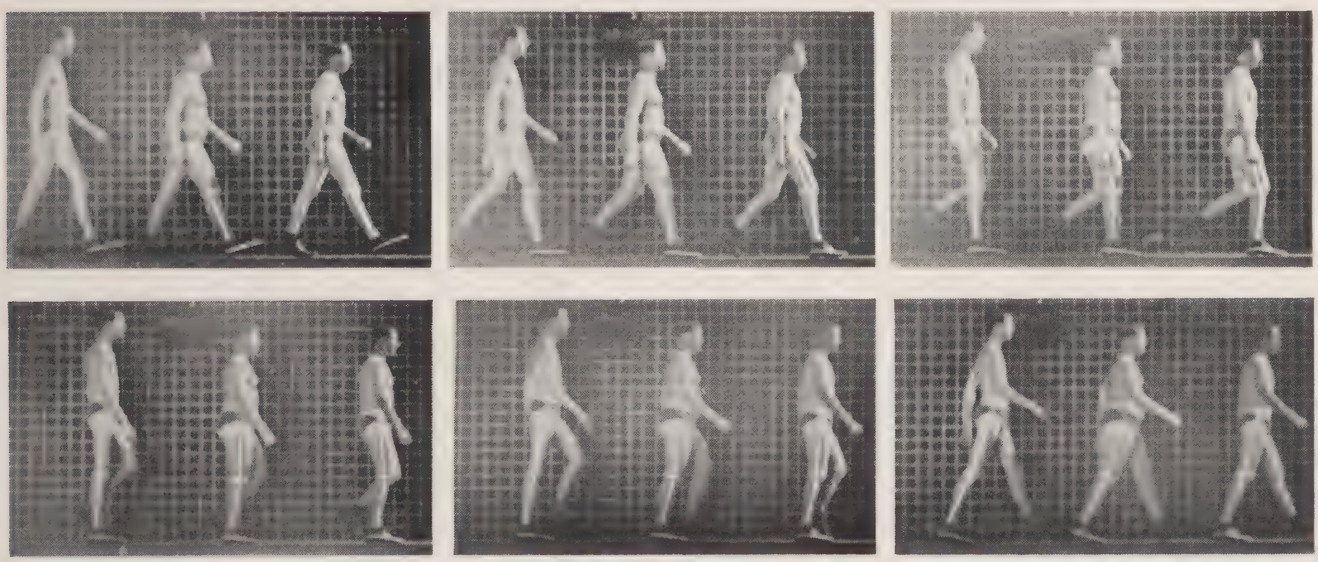


Fig. 47. Single frame enlargements from high-speed sixteen millimeter moving pictures at 700 frames per second showing two stages of knee lock.

observed from this photograph that the knee is locked as the heel strikes the ground, then unlocks and flexes slightly to cushion the shock of impact. The tibia then appears to remain nearly stationary while the femur rides over it until the second locked position is reached at the push-off stage.

In amputees the jerky action of the prosthesis is readily reduced to an observable motion by high-speed motion pictures and the tendency to roll or "vault" over the artificial leg becomes apparent.

(7) Pylon Studies. The pylon test program was initiated to obtain the order of magnitude of the forces acting on an artificial leg and to study the influence of the type of socket, alignment, and bumper stiffness on comfort as a function of these forces.

The pylon is a columnar structure which replaces the usual shank member in an artificial leg. Electrical strain gauges bonded to the pylon provide a means for obtaining a continuous record of the forces acting during the various phases of locomotion. These strain gauges employ a bonded metallic filament as the strained element and are connected in a Wheatstone bridge arrangement, the unbalance of which becomes a measure of strain. The resistance of the gauge wire varies with elongations or contractions of the gauge, which ultimately is recorded by an oscillograph from which forces and torques can be computed.

Six quantities have been measured on above-knee and below-knee amputees by this pylon test:

(a) Axial loads,
(b) Fore and aft moment near the lower end of the shank,
(c) Fore and aft moment near the upper end of the shank,
(d) Lateral moment near the lower end of the shank,
(e) Lateral moment near the upper end of the shank,
(f) Torque about the shank.

From these six quantities directly measured, shears in the fore and aft and lateral directions have been computed as have moments about the ankle and the knee. This has provided a complete force picture of the whole leg. In Fig. 48, the aluminum tubular pylon with strain gauges attached is illustrated. A set of pylon force data curves, Fig. 49, shows a comparison of forces acting on the artificial leg using a pelvic hinge socket and using a suction socket.

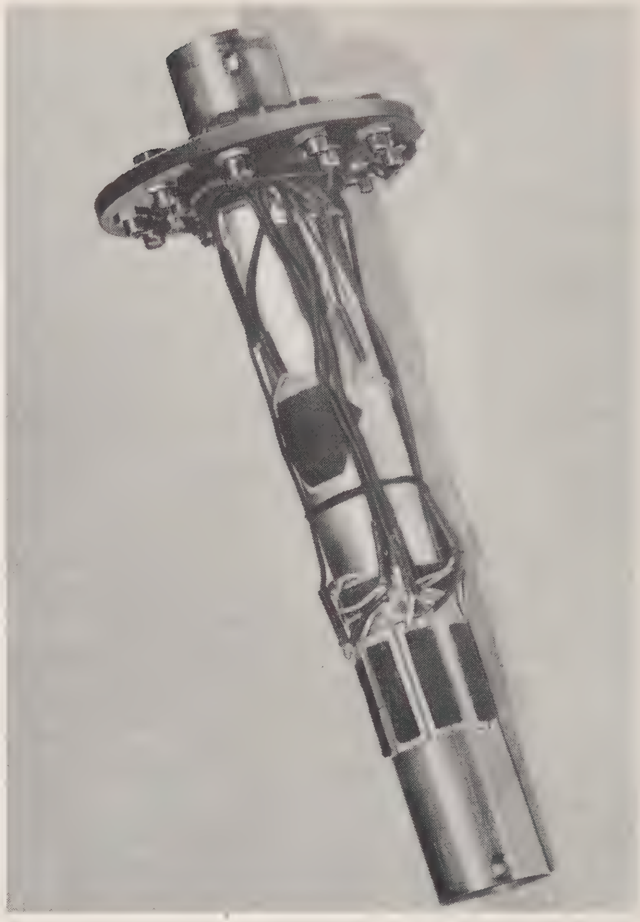


Fig. 48. Pylon with strain gauges attached.

In addition to the primary purpose of the pylon studies, the influence on forces of the alignment of the various segments of the leg was investigated. This phase of the project included the ankle rotation studies as well as the effect of sudden impact caused by jumping.

(8) Force Plate Studies. Since the pylon studies were limited to amputees, a method of measuring forces acting on the leg of normal subjects as well as amputees was considered necessary. For this purpose, a force plate was designed and built by Northrop Aircraft, Incorporated, to be used at the University of California for measuring floor reactions on the foot of normal subjects and amputees. Floor reactions were determined during level walking, walking up and down ramps and up and down stairs. The force plate measured vertical load, fore and aft shear, lateral shear, torque, and also served to estab-

lish the location of the centers of pressure on the foot while 35 millimeter motion pictures were taken simultaneously to establish the position of the segments of the body relative to the force plate.

When a normal subject or an amputee steps on the force plate the floor reactions transmitted to it produce strains in the supporting mechanism which are measured by electrical strain gauges (described in Project 7) and are recorded on an oscillograph tape. Floor reactions and center of pressure locations can be obtained from the oscillograph record by properly calibrating the force plate.

Fig. 50. University of California force plate.

Force plate data have been found useful for comparing the gait of amputees with that of normal subjects, for comparing various types of prostheses under similar walking conditions, for evaluating the influence of adjustments in the prosthesis on the forces astablished, and for identifying the individual peculiarities of gait. Data also have indicated that some amputees show partiality to their prostheses by the fact that the vertical loads on the artificial legs do not reach the body weight. For the normal subject the maximum vertical load has been shown to be as high as 180 per cent of the body weight during walking down stairs. Center of pressure data have provided means for evaluating gait characteristics, proper stiffness in a prosthesis, and alignment of the foot and ankle assemblies.

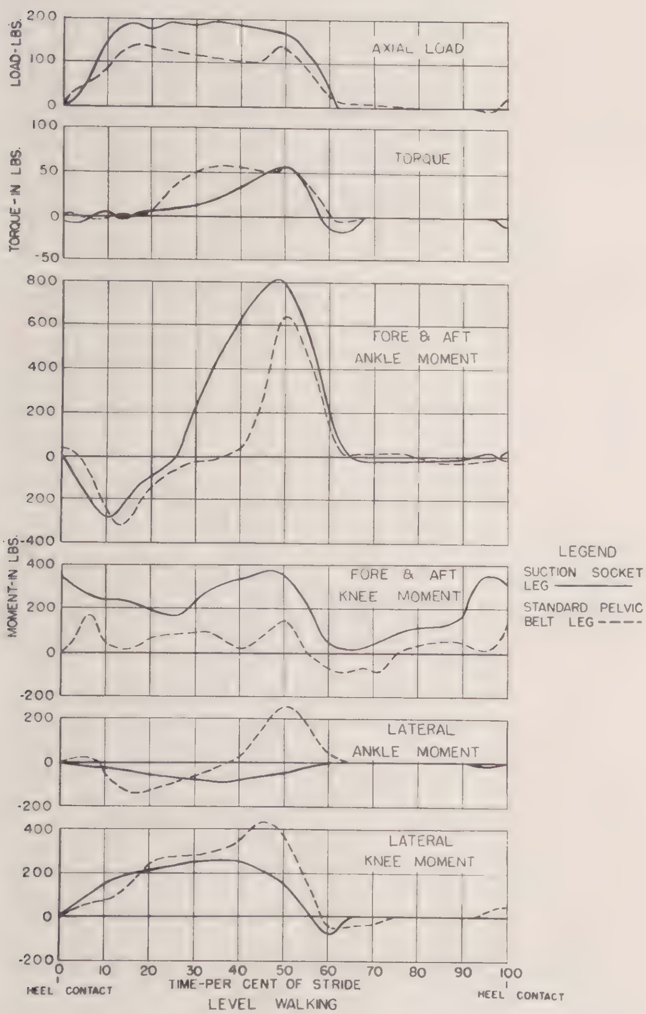


Fig. 49. Comparison curves for suction socket leg and standard pelvic belt leg.

Nonreproducible data, caused by erratic actions developed in the first experimental force plate, have led to the design and construction of a new force plate at the University of California which embodies no frictional surfaces, no moving parts, and permits more accurate data to be recorded. In Fig. 50, a photograph of this new force plate is shown. Two such force plates are now in use at the University of California. A typical set of force curves is shown in Fig. 51, and Fig. 52 illustrates typical center of pressure diagrams.

(9) Limb Alignment. Because of a general lack of agreement among limb manufacturers regarding optimum positions of the various elements of the leg, an adjustable below-knee and an adjustable above-knee artificial leg were designed and constructed. Determination of such factors as the best positions for the axes of the ankle and knee joints, the effect of changes in the positions of these elements on comfort, the ability to walk, and gait characteristics has been made.

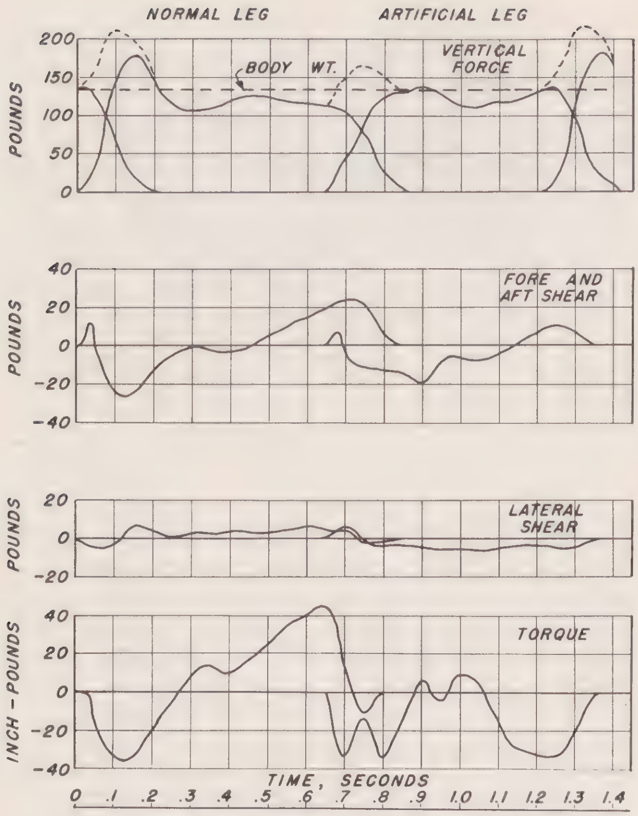


Fig. 51. Floor reactions on the foot taken from force plate measurements.

A sketch of the below-knee adjustable leg is shown in Fig. 53, with explanatory notes on the adjustments. In addition to the adjustments of the below-knee leg, the above-knee leg may be adjusted for upper leg length, angle of the knee axis relative to the vertical plane of progression, lateral position of the weight-bearing line, and angle of the shank relative to the vertical position in a lateral plane.

An effort also has been made from this study to subdivide the elements of the prosthesis into three groups:

(a) Elements which have little or no effect on comfort and gait,

(b) Elements which have the same optimum position for all amputees, the locations of which can be fixed within given tolerances on all prostheses,

(c) Elements, the optimum positions of which vary with individual characteristics of the amputee and must be determined in the limb fitting process.

(10) Suction Socket Program. The program supported by the Committee to obtain information regarding the suction socket method of fitting above-knee artificial legs, of which a detailed explanation appears elsewhere in this report, has had the University of California as one of its participants.

Eight subjects, having various types of stumps, were fitted and, with one possible exception, each is wearing the suction socket leg to the exclusion of

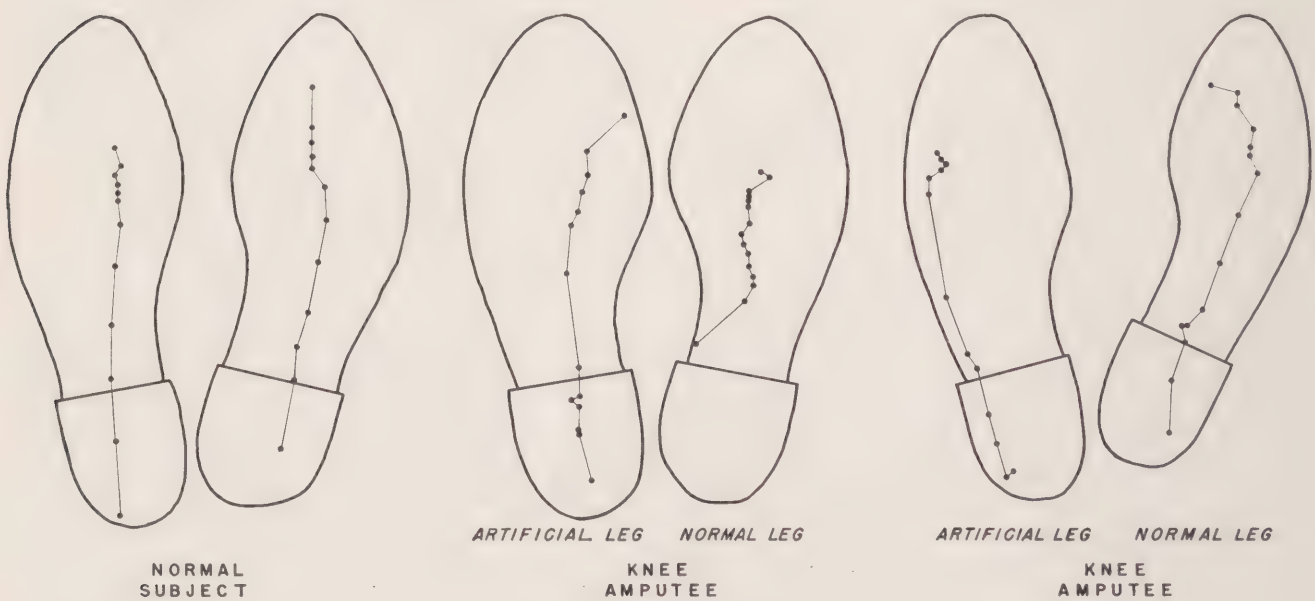


Fig. 52. Center of pressure data.

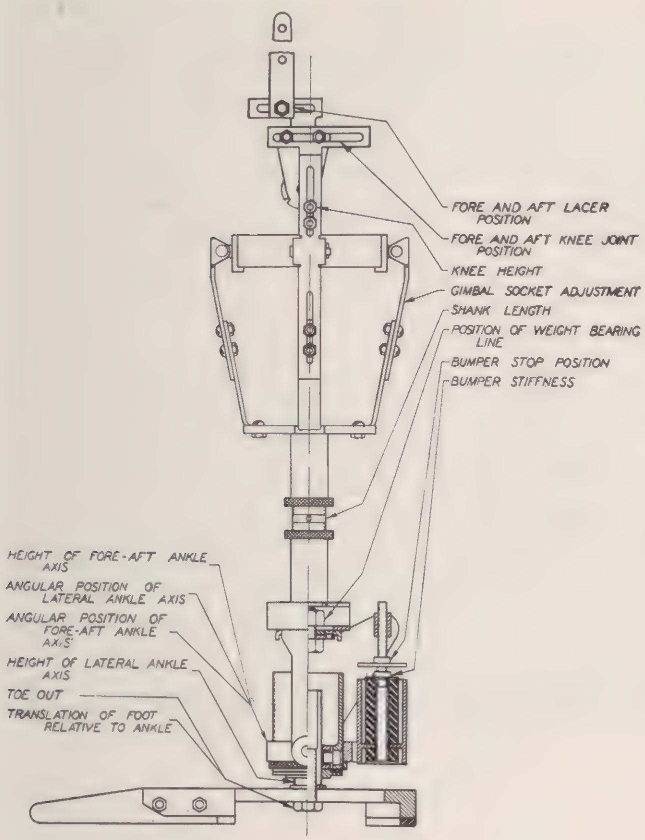


Fig. 53. Below-knee adjustable leg.

his old type leg. A log of pertinent information has been recorded for each subject, particularly detailing the changes that were necessary in the fitting of the socket or in the alignment of the leg.

Some interesting information has been secured in addition to that requested from limb manufacturers participating in the suction socket program. Moving picture records have been made during various walking maneuvers, and Kodachrome transparencies have been taken of most subjects in an effort to detect possible color changes as indications of circulatory changes resulting from wearing the suction socket. An effort has been made to study the effects of the lowered pressures inside the socket on blood circulation in the stump. Records have been made, by means of high-speed motion pictures, the glass walkway, and the force plate to determine any apparent changes in the functional use of the prosthesis. Pressure variations in the socket during locomotion have been recorded, and several different types of valves have been tried in the socket to determine the best method of control of pressure. Considerable experimenting has been done with the shape of the suction socket. The first three were rectangular in shape, with the first two being cut lower under the gluteus maximus than the ischial seat and having little or no roll across the anterior face. Subsequent ones have been more triangular in shape with the small side placed medially and with a gradual rise from the ischial seat to the great trochanter. Best results have been obtained with the height of the lateral side slightly below the greater trochanter and a roll across the anterior side. Roll locations, relief for the gluteus maximus, and shape of the ischial seat have been given careful consideration.

The effect of torsional rotation of the socket has been troublesome but apparently has been eliminated by the use of a mechanism at the ankle permitting rotation to occur there rather than between the socket and the stump.

In Fig. 54, a practical design of an automatic expulsion suction socket valve is shown.

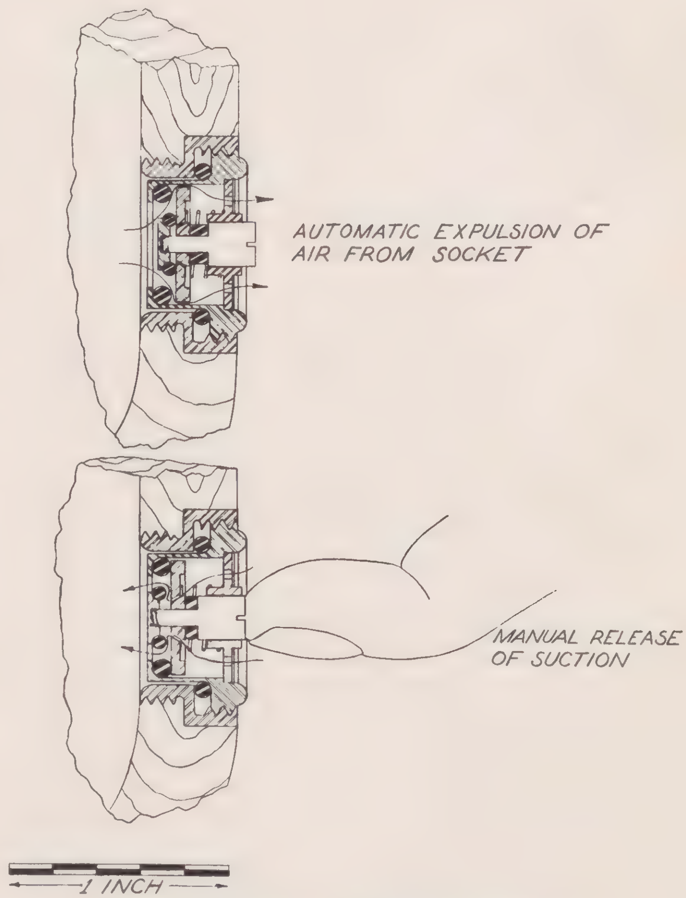


Fig. 54. Automatic expulsion suction socket valve.

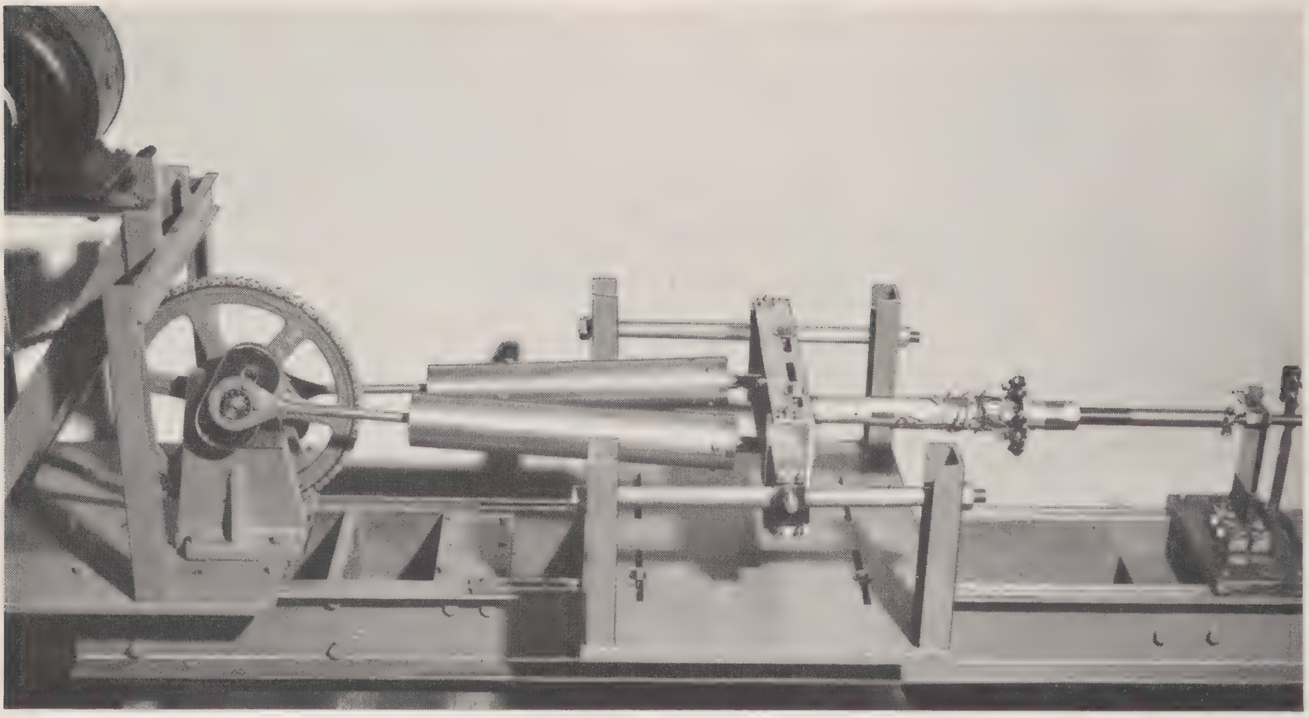


Fig. 55. Accelerated below-knee leg tester.

(11) Materials Testing. The use of laminated plastics in artificial limbs seems indicated because of high strength-weight ratios and high stiffness-weight ratios as compared to other available materials. They may be used as structural members, as strengthening and stiffening agents for weaker materials, or for waterproofing and finishing surfaces. Because various organizations testing plastics under the Committee auspices were not following a completely uniform testing program, it was thought advisable to develop suitable testing standards for use in the artificial limb field.

Specifications of the American Society for Testing Materials covering this field as well as those available under Federal sponsorship were reviewed carefully and modified where necessary to provide a set of tests applicable to the uses of plastics in the artificial limb. Subsequently a set of testing specifications were written and adopted covering the following tests:

(a) Compression,
(b) Tension,
(c) Bearing,
(d) Flexure,
(e) Creep at normal and high temperatures,
(f) Brittleness (impact) at low temperatures,
(g) Punching shear,
(h) Flexural fatigue,
(i) Flammability,
(j) Joint strength (for adhesives).

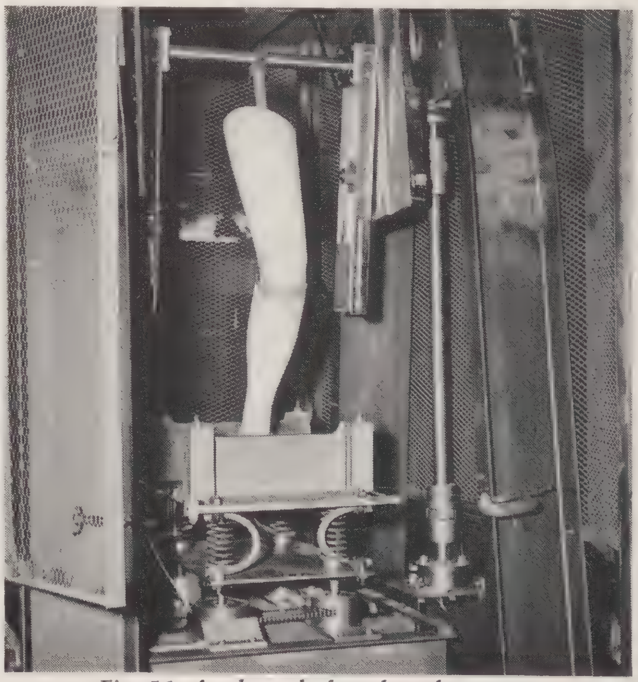


Fig. 56. Accelerated above-knee leg tester.

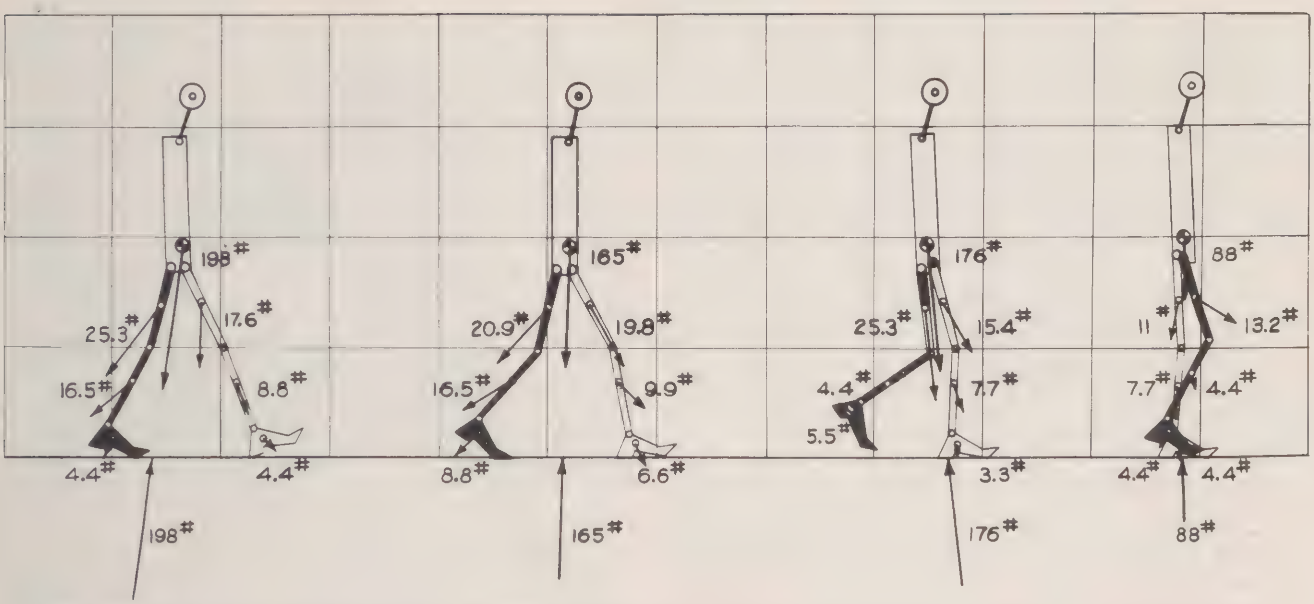


Fig. 57. Four phases of body position in walking showing forces acting at the centers of gravity of the segments of the leg and the floor reactions.

Of these tests, those covering tension, compression, and bearing were used for an initial evaluation of the mechanical properties of the plastic; the remainer of the tests was run only on those plastics and laminating fabrics selected as also being satisfactory from the point of view of all applicable properties.

In addition to the properties listed above, such factors as handling ease, fabrication difficulties, storage properties, "pot life," availability, and cost were considered in comparing all the plastics.

Experience in this testing program has led to the recommendation of the following tests to investigate further the mechanical properties of the more outstanding laminated plastics:

(a) Static and fatigue flexure tests of tubular specimens,

(b) Creep of a tension strip under stress of 10,000 pounds per square inch at a temperature of 100 degrees Fahrenheit,

(c) Impact tests (dropping a ball on a flat plate, six inches square, clamped on all four edges),

(d) Weathering tests,

(e) Modified Rockwell hardness tests.

It seems important also to test joint strength of laminated plastics with both riveted and bonded joints.

(12) Accelerated Testing. A correctly designed artificial limb should withstand not only the maximum loads to which it may be subjected but also must endure these loads when used constantly over an extended period of time. For the purpose of conducting an accelerated life test, several machines were devised under Committee supervision which would approach the natural loading of the artificial leg during walking. Three years was assumed to be an acceptable minimum life of an artificial leg, and it was estimated that three million steps would be made with the leg in this period of time, based on about two miles per day.

Two such machines were built at the University of California. In one, the below-knee leg tester, shown in Fig. 55, the shank, ankle, and foot assembly of the artificial leg are placed under loads analogous to those experienced in normal walking and the specimen is subjected to the equivalent of the suggested three years of normal service in about twelve days. The above-knee leg tester, Fig. 56, requires about seventeen days to complete the equivalent three year test, during which time normal loading and movement are experienced by the limb.

(13) Structural Design. To achieve an efficient and effective structural design of an artificial leg, it seemed necessary to determine accurately the external forces acting on the leg and the manner in which these forces were transmitted to the body. In this project on design, data obtained from interrupted light studies, pylon tests, and force plate measurements were analyzed to determine such criteria.

In Fig. 57, forces acting on the leg in four phases of body positions in level walking are shown. The arrows indicate the resultants of gravitational and inertial forces acting at the center of gravity of the leg segments. Note the variation in magnitude of the floor reactions on the foot of the subject: for the 151 pound subject, the maximum value of floor reaction is 198 pounds and the minimum value 88 pounds. This large variation primarily is ascribable to the high speed of walking in this particular test.

Results evolved from the study of structural design have been enlightening. Comparisons of forces acting on the shank have indicated very marked differences between normal subjects and amputees. The curves showing bending moments of the knee indicated clearly the locking and unlocking of the knee joint of a normal subject during the stance phase, whereas no unlocking of the knee joints of amputees was noted. The curves showing bending moments at the ankle have indicated that lack of motion in the prosthetic foot following heel contact resulted in high moments which are not experienced by the normal subjects. This lack of motion is attributable to the stiffness of the rear bumpers.

It has been emphasized that critical conditions were not assigned to design loads used for calculating the required ultimate strengths in prostheses; unusual conditions in locomotion such as recovery from fall, jumping, or lifting of heavy weights may result in higher loads than indicated below. Also no consideration has been given to an adequate and practical factor of safety. The following observed loads have been indicated on the bases of available data for normal subjects:

(a) Maximum axial load occurs in the down-ramp condition during the "foot flat down" phase with a value of approximately thirty-three per cent above the weight of the subject,

(b) Maximum positive ankle moment occurs in the up-ramp condition during the "heel rising" phase just preceding toe-off and is calculated at 940 inch-pounds. This value does not seem to depend upon the weight of the subject,

(c) Maximum negative ankle moment for the normal subject takes place during level walking and has a relatively small value of 220 inch-pounds. Maximum negative ankle moment of amputees varies from that of the normal subjects as it depends largely on the stiffness of the rear bumper in the foot. For an amputee it occurs during down-ramp conditions and reaches a value of 500 inch-pounds,

(d) Maximum positive moment at the knee is higher for amputees than for normal subjects. An amputee walking up-ramp develops a positive moment about the knee of 930 inch-pounds, while in a normal subject it does not exceed 180 inch-pounds,

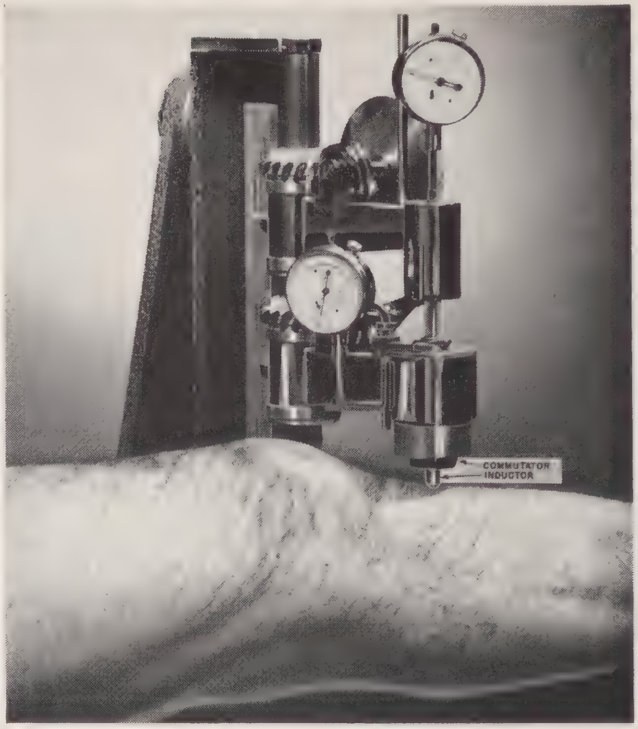


Fig. 58. Dolorimeter.

(e) Maximum negative moment at the knee of the normal subject is somewhat higher than that of the amputee, since the amputee can resist only a small amount of negative moment. For a normal subject it occurs during walking upstairs and reaches a maximum value of 1460 inch-pounds, while for an amputee it occurs during walking down-ramp and does not exceed 350 inch-pounds.

(14) Pain in Relationship to Amputation Stumps. The most common complaint of the amputee is pain. It may be severe or moderate; it may appear soon after application of the prosthesis or arise only following prolonged use. Some of the factors in the production of pain are obvious, such as a poorly fitting socket with excessive pressure on or abrasion of the stump. Other causes may not be so evident or so easily rectified. Pain may limit the use of the prosthesis or even may lead to the abandonment of the appliance. Because of the seriousness of pain in the life of the amputee, some effort was devoted to the study of painful stumps so that the improved artificial limb might be used fully.

Since an adequate understanding of the basic mechanisms transmitting pain was necessary before a satisfactory attack could be made upon the problem of its control, a detailed investigation was begun of the nerve supply of the tissues and their response to stimuli of a nature similar to those arising in the stump of the amputee. This study was divided into two main branches: (a) histological investigation, the microscopic study of tissues, and (b) a physiological investigation, dealing with the types of stimuli producing pain in the deep tissues.

The response of the tissues to stimuli similar to that experienced by the amputee was studied by means of apparatus called a dolorimeter which permitted a controlled amount of pressure to be applied over a small area. The results of these applications showed some variations in the pain threshold of the various areas tested. Preliminary results show a strength duration curve which resembles that obtained upon stimulation of a mixed nerve trunk. In Fig. 58, the dolorimeter is shown in action, and Fig. 59 gives the average values of pressure obtained for each point on fifteen subjects.

From the investigation thus far, the pain experienced in amputation stumps due to the prosthesis resembles the slow pain elicited from the deep tissues. It is hoped that this rational study will result in a remedial design of the socket, lessening the pressure on painful parts.

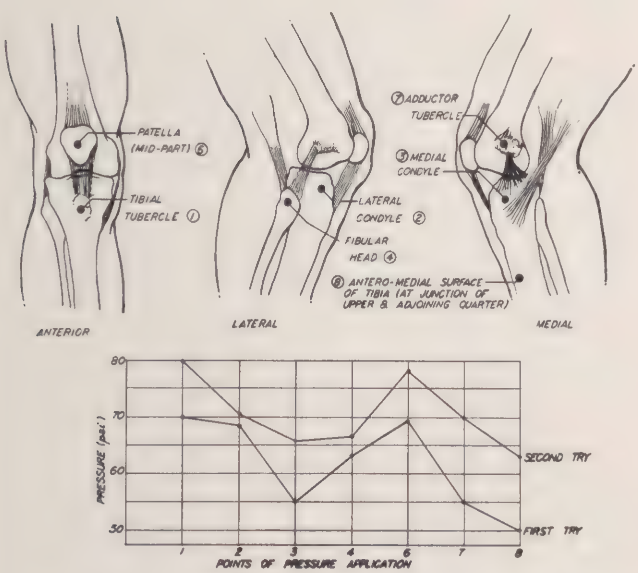


Fig. 59. Dolorimeter results averaged on fifteen subjects.

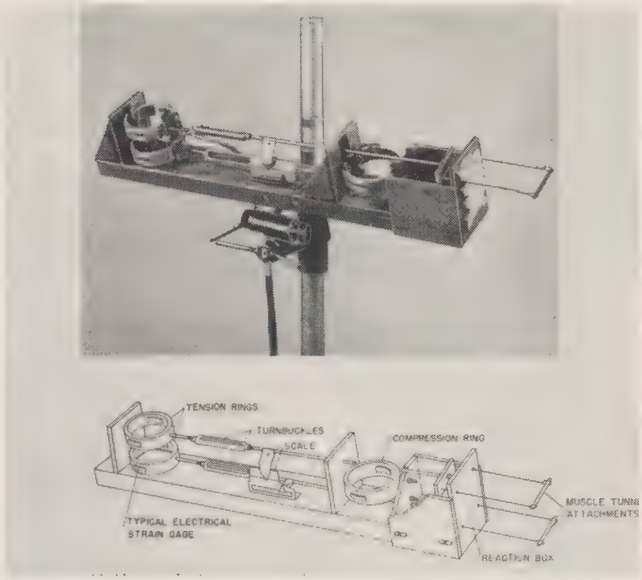


Fig. 60. Muscle dynamometer.

(15) Muscle Dynamics as Related to Cineplastic Amputations. The revival of interest in the cineplastic method of using muscle tunnels to create forces to operate artificial arms made the knowledge of the characteristics of muscle contraction essential if full utilization of the prosthesis was to be realized. As mentioned in the project covering the cineplastic method, six German and two American amputees representing a wide variety of muscle tunnels were available for tests.

The relationship of muscle length to active tension was determined on a dynamometer which restricted muscle shortening and gave pure isometric tension values. In Fig. 60, the dynamometer is illustrated.

A study was made also of the ability of the muscles to shorten against increasing loads. Results of these tests were plotted as load-excursion curves revealing a near-linear relationship between the load in tension and the distance the muscle could shorten, that is, the greater the load, the shorter the distance the muscle could move it. In the isometric muscle tension curves a similar relationship indicated that as the muscle length increased, the force that could be developed increased also.

From this study the implication seems clear that maintenance of adequate muscle length during active contraction is important if functional adequacy is expected with cineplastic prostheses; further, the incorporation of compensatory mechanisms, such as force multipliers, is indicated in such a prosthesis.

The importance of maintaining adequate muscle

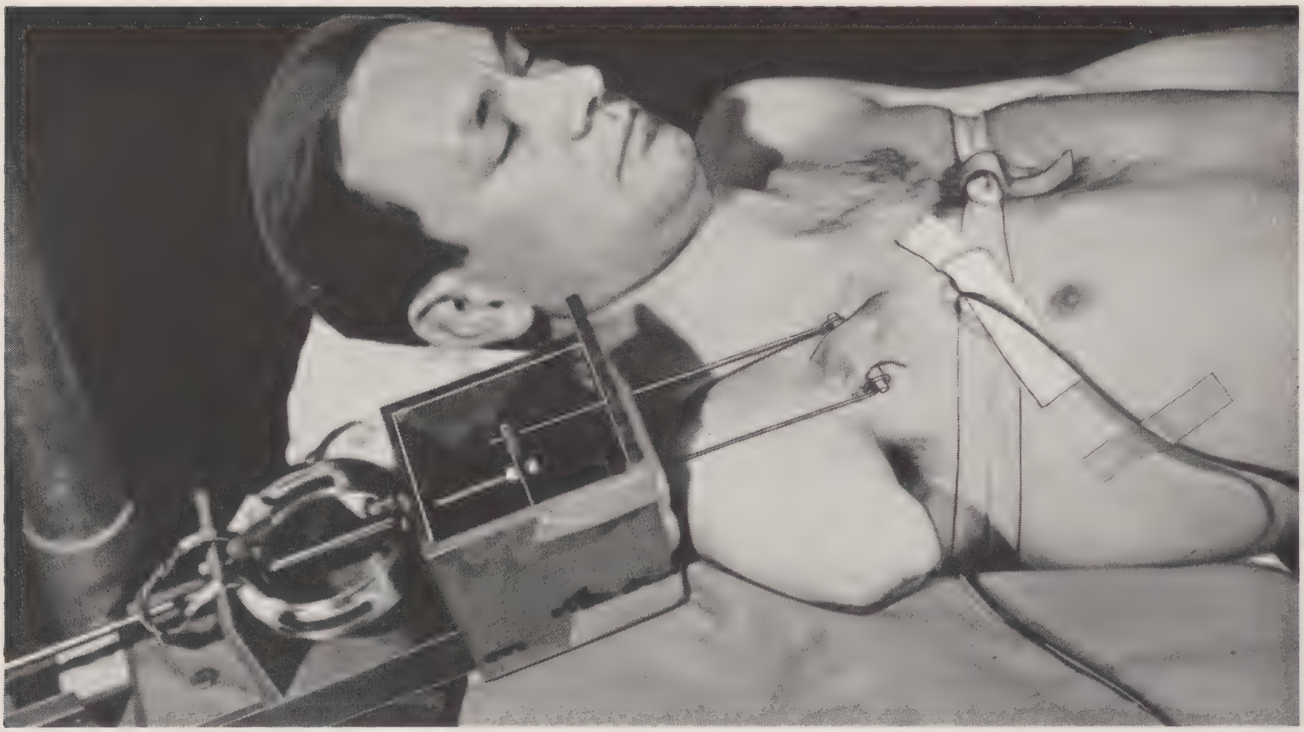


Fig. 61. Dynamometer in use on pectoral muscle motor.

lengths should be borne in mind by the surgeons performing the original amputations as well as those perfoming the cineplastic operations. Indications from the muscle diagrams are that muscle shortening prior to the cineplastic operation jeopardizes its ability to contract and, therefore, to exert a satisfactory external force. A muscle dynamometer is shown in Fig. 61, in use on the pectoral muscle motor of an arm amputee. Checking with the electromyograph, whose leads are shown, insured that the amputee consistently exerted the same effort.

(16) Anthropometric Survey. The purpose of this project was to collect information on a sufficiently large sample of adult men and women so that the length, transverse dimensions, and circumferences of the arm, the leg, and their respective upper and lower components could be defined. The study assumes that the average values obtained represent a "normal" arm or leg. The variations in these dimensions also were to be determined. The "normal" arm and leg can be used, therefore, as a starting point for determining the interrelationships between the varying dimensions followed by the establishment of size categories representing a series of standardized limb sizes. A further assumption involved here is that amputees may be considered a random sample of a "normal" population insofar as their limb dimensions are concerned. This assumption may lack some validity because of changes in stump dimensions after amputation, but should not affect the problem of matching the opposite limb by the below-elbow portion of an above-elbow arm, for example.

The age, weight, height, and forty-two additional measurements were recorded for a white adult male group of 1,840 individuals consisting of 360 soldiers, 500 sailors and marines, 750 male college students, and 230 adults over thirty years of age. Similar measurements were recorded for 1,160 women, of whom 300 were WAVES, 640 college students, and 230 adult women over thirty-five years of age. Negro males to the number of 240 were measured also, but nonwhite groups other than Negro were too few to give reliable size indications and are excluded from all tabulations.

The final report of this subcontractor will contain a statement and analysis of the linear dimensions, their averages, and the variability of these constants. Particular consideration is being given to size factors involved at the knee and ankle, elbow and wrist.

UNITED STATES PLYWOOD CORPORATION

New Rochelle, New York

BACKGROUND. Shortly after the Committee on Artificial Limbs was formed the United States Plywood Corporation was asked to evaluate the use of plastic laminates for artificial legs. This investigation was made to determine the materials having the most suitable physical and molding properties and to develop molding methods of mass producing laminated shanks, thighs, and stump sections. The project, started in September, 1945, under the direction of Mr. Herbert E. Ennis, project engineer, and with the guidance of Mr. O. S. Tuttle, chief engineer, was terminated in May, 1947, with a successful completion of the work undertaken.

PROJECTS. ***(1) Evaluation of Plastics.***

(a) The first problem undertaken by this subcontractor was the study of physical properties important in the evaluation of plastic laminates for artificial legs. A fundamental property required of any material to be used in a crustacean shank or thigh construction is a high strength-weight ratio when subjected to compressive loads. To make these tests, tubular specimens having thin walls were laminated from cloths of Fiberglas, cotton, nylon, and rayon as reinforcement fillers of various constructions, pre-treatments, thicknesses, weaves, and weights. These were combined with various standard polyester resins and tested under compressive loadings. The most suitable materials then were further tested to determine their tensile, bearing, shear, impact, and flexural fatigue strength. Stability, durability, cost evaluation and ease of manufacture also were considered as were the ability to resist moisture and the deleterious effects of extreme temperatures. In addition, a number of specimens of the various materials previously tested were exposed to fungus and high humidity in a tropical test chamber. Extensive fatigue tests were made on specially designed samples in a machine of the rotating beam type, which maintained a constant bending moment throughout the full length of the specimen.

For structural parts, such as shanks or thighs, a thin Fiberglas cloth having an eight-harness weave and a special finishing treatment for laminating was found to have the most desirable properties of all the cloths tested. For molding stump sockets or other nonstructural parts, rayon stockinette or cotton tape were recommended because of light weight, dimensional stability, ease of machining and compatibility with the skin.

A number of commercial polyester resins were found satisfactory, the choice depending upon the individual molding technique used.

(b) A second problem encountered in the evaluation of plastics was the selection of suitable adhesives capable of bonding the plastic laminates to the metal ankle and knee fittings under conditions of moderate temperatures and pressures. Several standard metal-to-metal bonding adhesives of both thermosetting and thermoplastic types were investigated by subjecting specimens to shear tests. The most suitable adhesives found were used in the accelerated service tests of shank sections.

(2) Molding Methods. A study of low pressure molding methods of producing artificial limbs was made in an effort to reduce present limb costs, permit greater production, and aid the various hospital centers and limb manufacturers. Two fundamental methods of attacking this problem were used. The first made use of a male mandrel or mold, a positive form on which the plastic composition was placed and from which it took its shape. This method resulted in a smooth inside surface of the finished product, but required some machining of the outer surface. The second method used a female mandrel resulting in a smooth outer surface, but required costly permanent molds.

The choice of a molding method depends upon the facilities available, the rate at which parts are to be manufactured, and the total number of parts of one size to be made. The method of molding laminated shanks and thighs on male mandrels of either wood or plaster using form-fitting cauls or lining materials and molding in a hot air oven apparently is the most satisfactory method for limited production in either small shops or hospital centers. While the cost of producing standard shank sections can be reduced by using the female mandrel molding method, much more expensive tooling and costly equipment is needed to establish the shop and this method should be used only for large production of a few standard sizes.

For either of the methods of molding structural shanks and thighs, five layers of Fiberglas cloth (No. 181-14) impregnated with a polyester resin was recommended. It was necessary to add additional cloth, usually three layers, where a bearing load,

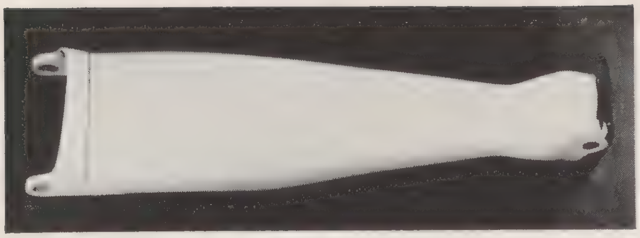


Fig. 62. Plastic laminated shank bonded to standard Army aluminum ankle fitting and commercial knee fitting.

such as that due to riveted joints, was imposed. This gave a high factor of safety with light construction.

(3) Testing of Molded Parts. Five plastic laminated shanks were molded from materials selected from the evaluation of plastics study and were bonded to a standard Army aluminum ankle fitting and a commercial type knee fitting. The illustration, Fig. 62, shows one of the finished shanks.

Three of the shanks were tested at Northwestern University in a leg testing machine which applied end compression and repeated bending loads and which is described elsewhere in this report. From these tests, made under varying load conditions, the conclusion was reached that the laminated structures and the bonding methods used for both the ankle and knee fittings were satisfactory for actual service use.

The remaining two shanks were tested in the walking machine at the Army Prosthetics Research Laboratory at Walter Reed Hospital in Washington, D. C. This machine attempted to simulate actual walking on uneven ground and a dead-load weight of approximately 250 pounds was applied during each test. Here again, in each test an indication of the weakness of the metal fittings presented itself. The shank and the bond to the ankle and knee fittings withstood the tests without failure.

INTERNATIONAL BUSINESS MACHINES CORPORATION

Endicott, New York

BACKGROUND. For many years the International Business Machines Corporation has maintained a policy of making jobs available to physically handicapped persons and in assisting wherever possible in their rehabilitation. This company also has amassed great skill and has exercised much ingenuity in the development and manufacture of intricate mechanical devices. For these reasons Members of the Committee sought help from Mr. Thomas J. Watson, President of IBM, and invited his participation in the program.

The emphasis in this project was placed on the development of entirely new devices rather than on mechanical improvements of existing arms and hands. Basic improvements in artificial arms required that new sources of power be developed, together with smooth and effortless means for control. Internal power sources, which were sources on the body itself such as the stump, shoulder, chest, abdomen, leg, foot, and use of body weight, were considered in great detail. Sources of external power considered were energy reservoirs which could be carried on the body. A study of these included dry cells, storage batteries to actuate electric motors, and pneumatic tanks; carbon dioxide cartridges and dry ice generators were excluded as being impractical. From these considerations electrical, pneumatic, and hydraulic methods were selected for development.

Mr. Reynold B. Johnson, senior development engineer at the IBM Endicott laboratories, undertook preliminary experiments for the development of pneumatic drives for operating an artificial hand. Mr. Samuel W. Alderson, a research physicist, directed the electrical arm project, and Mr. V. O. Wilkerson led in the development of the hydraulic mechanism. Mr. W. W. McDowell, manager of the engineering laboratory at Endicott, gave valuable help to the entire project.

As the artificial arm problem was analyzed, the need for closer contacts with a large number of amputees quickly became apparent and in October, 1946, a laboratory was set up in cooperation with the New York University College of Medicine at Bellevue Hospital, New York City. This laboratory, under the immediate direction of Mr. Alderson, was devoted to problems of arm suspension and control, and to motion analysis. In order to have dependable criteria for new developments, it seemed necessary to determine the basic causes for the inadequacy of conventional artificial arms, and studies of this problem were made at the Bellevue laboratory by interviews, observations, and detailed tests of the performance of amputees equipped with various types of arms.

PROJECTS. ***(1) The Electrical Arm.*** The first model of the electrical arm to be designed and constructed was an above-elbow arm with a single motor

drive and an electromagnetic power distribution device to serve the different joints. Suitable joint locks were provided as a part of the distribution mechanism. This first model, shown in Fig. 63, represented a concrete, but experimental solution to the various problems of electrical arm design. It included an arm flexion joint at the shoulder, an upper arm rotation joint, an elbow, a pronation joint in the forearm section, wrist flexion, and a fully articulated hand. Each of these joints could be operated independently at the will of the amputee by a combination of shoulder lift and stump motion actuating microswitches which started the motor and energized selected electromagnets. This arm was suspended by a metal support, extending up from a pivot on a hip plate, which was held in place by a belt. The upper part of the suspension was held in place by another belt encircling the wearer's chest and back, and the batteries necessary to operate the arm were attached to this belt.

After some basic research in suspensions and control methods was completed and after many improvements were made on the motor, the storage batteries, the clutches, locks, and overload devices, a second model electrical arm was designed. This consisted of four actively driven joints: an elbow, a pronation joint, a wrist flexion joint, and a partially articulated hand. In Fig. 64, these four joints can be identified clearly. The redesign of the entire mechanism lead to a more compact and lighter arm, and the alteration of the control mechanism provided a more easily learned system which was unaffected by changes in the arm or body position of the amputee. The hip plate suspension was redesigned to insure full freedom of the body and to increase the efficiency of the arm. The motor in this second model was placed in the forearm shell with direct gearing to the elbow and to the pronation joint. The wrist flexion drive passed through the pronation joint by a central shaft and a lock was placed at the joint, providing a free clutch, so that complete uncoupling was obtained. The finger drive employed a central shaft within the drive tube for wrist flexion; a bevel gear differential was used to cross the wrist flexion joint. A lock was placed in the hand and the clutch left free, so that no coupling existed between the hand and the two moving joints.

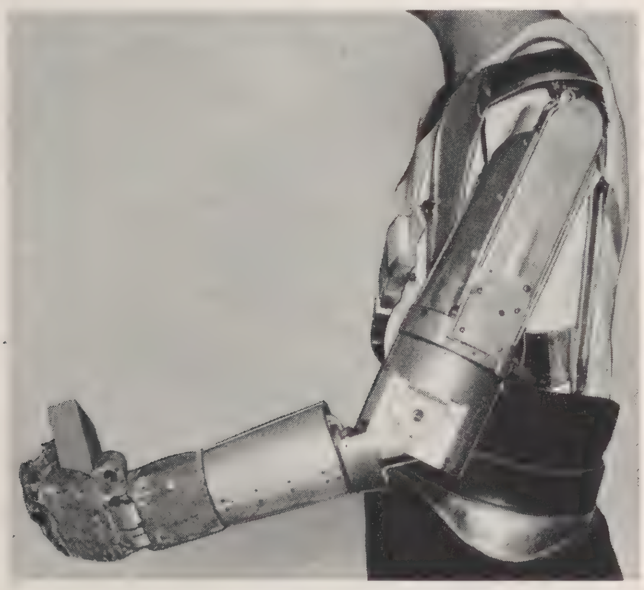


Fig. 63. Experimental electrical arm, model one.

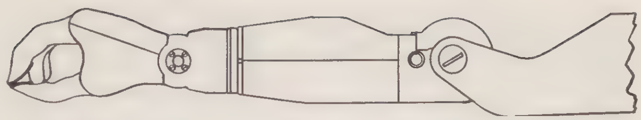


Fig. 64. Experimental electrical arm, model two.

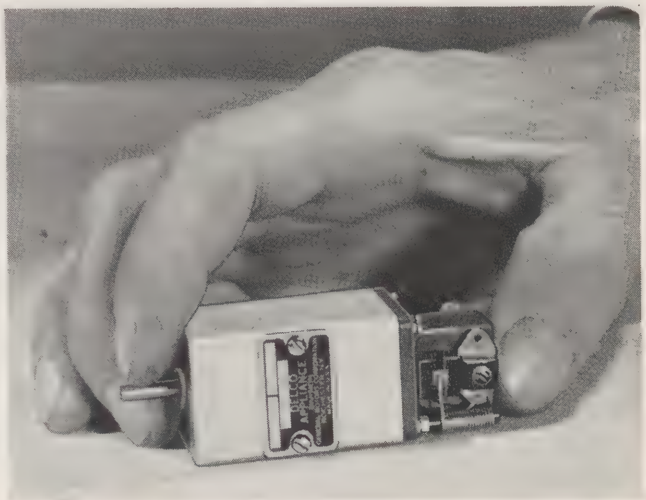


Fig. 65. Permanent magnet motor.

Much of the time and effort spent on this project was expended on the development of component parts going into the redesigned arm mechanism. The Delco Appliance Division was helpful in redesigning the permanent magnet motor to improve the motor characteristics. The magnetic structure, the windings, and the housing were altered to fit the motor into the arm in a more efficient manner. The redesigned motor, shown in Fig. 65, weighed 5.3

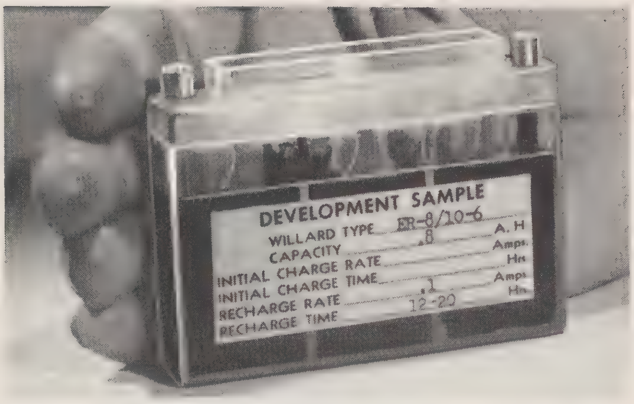


Fig. 66. Willard rechargeable battery for electrical arm.

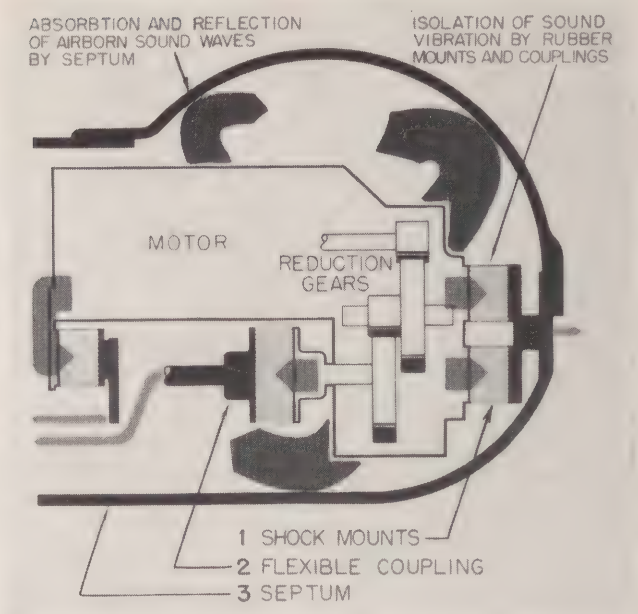


Fig. 68. Methods of soundproofiing arm mechanism.

ounces and gained a maximum efficiency of sixty-five per cent at a speed of 9,200 revolutions per minute with a corresponding torque of 0.8 inch-ounces.

Leak proof rechargeable batteries, one of which is shown in Fig. 66, were developed specifically for this project by the Willard Battery Company. They were packed in a nylon battery pouch and attached to the arm harness. These batteries were intended to be recharged on alternate days and were estimated to have a service life of three years. According to the calculations based on actual amputee usage, one set of completely charged cells should permit normal operation of the electrical arm throughout an entire normal day.

Other mechanisms such as gears, clutches, locks, and over-load devices which connected the various arm joints to the motor had to perform the following distinct functions: (a) reduce the motor speed to working arm speeds, (b) subdivide the motor power into separate drives to the different joints, (c) provide electrical means for the independent selection of each drive, (d) provide locks to resist the internal forces at the joints, and (e) safeguard the motor and gears against excessive external loads. An electromagnet was required to engage each clutch and a selector mechanism actuated these electromagnets. To give an idea of the size and complexity of these mechanisms, Fig. 67 illustrates a clutch and selector unit.

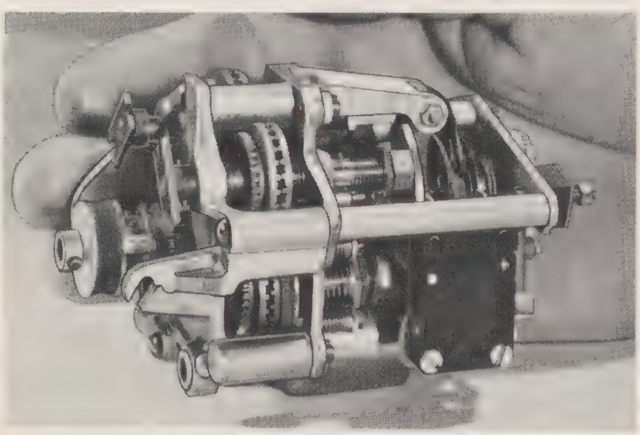


Fig. 67. Clutch and selector unit.

One of the most fundamental problems in the development of the electrical arm was that of reducing the noise from the motor and the various mechanisms to a satisfactory level. The principle means for reducing the sound level was to isolate sound vibrations and prevent them from passing through to the outside of the arm. In Fig. 68, this basic technique is schematically illustrated. All noise producing elements were mounted on rubber and the entire mechanism within the housing, or septum, was completely sealed so that direct air paths were closed to the airborne sound waves. When sound waves struck the walls of the septum, the energy was reflected back into the mechanism chamber and eventually absorbed in the material of the walls, resulting in only a small part of the energy passing through the walls to produce audible sounds.

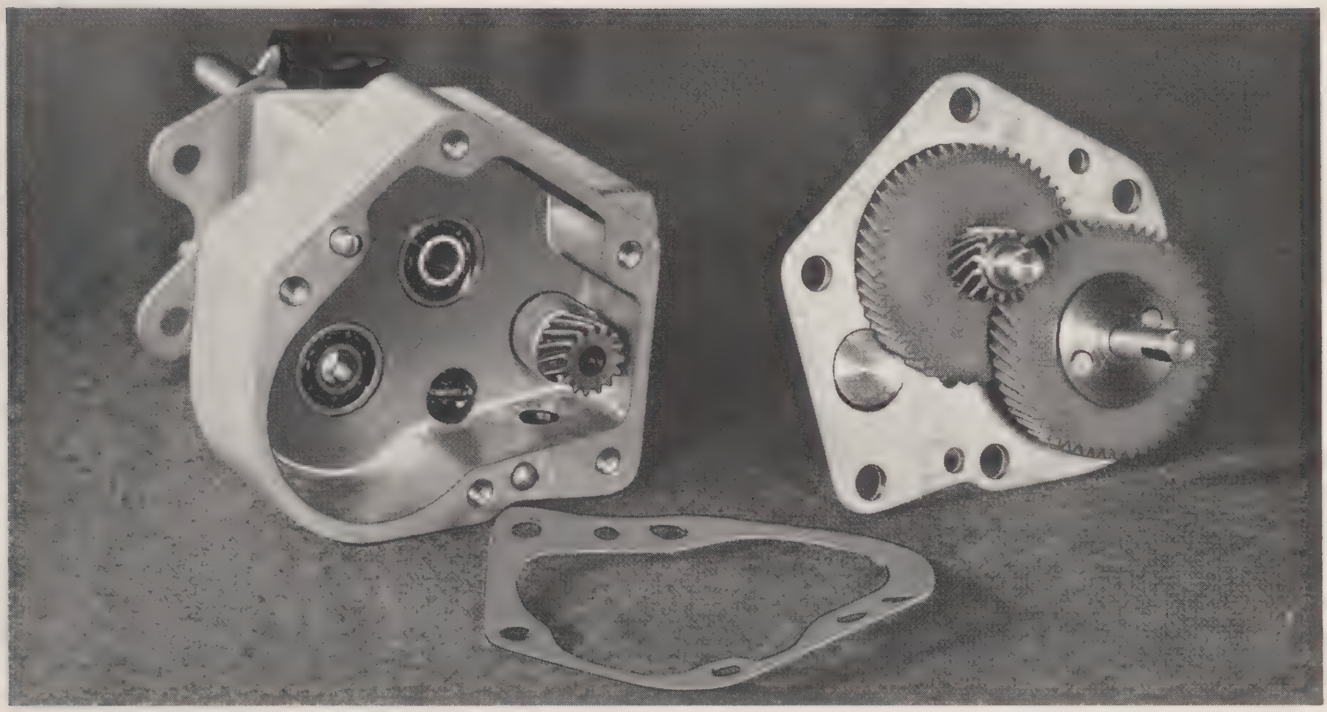


Fig. 69. Motor gear reducer with cover removed.

The reduction of the motor speed to that of the output shaft was accomplished by two pairs of gears. In Fig. 69, the motor gear reducer is shown with its magnesium cover removed exposing the internal gear mechanism. Miniature ball bearings were used on the intermediate and output shafts.

Descriptions of the various control mechanisms which were designed and tested for use with this arm are too numerous and complicated to include here. One combination, that of control by the muscles of the abdomen and biceps, is illustrated in Fig. 70, tests of which gave indications of ultimate success.

While the electric arm was designed primarily for an above-elbow amputee with an average stump, experiments have indicated that amputees with shoulder disarticulations may be adequately served by such a device. Although the arm mechanisms have been completed and preliminary operation of the units have indicated that the design was mechanically successful, extensive service tests have not yet been made. The final test model weighed approximately three and one-half pounds, which was considered a practical weight, and control of the arm has proved to be simple, accurate, and effortless.

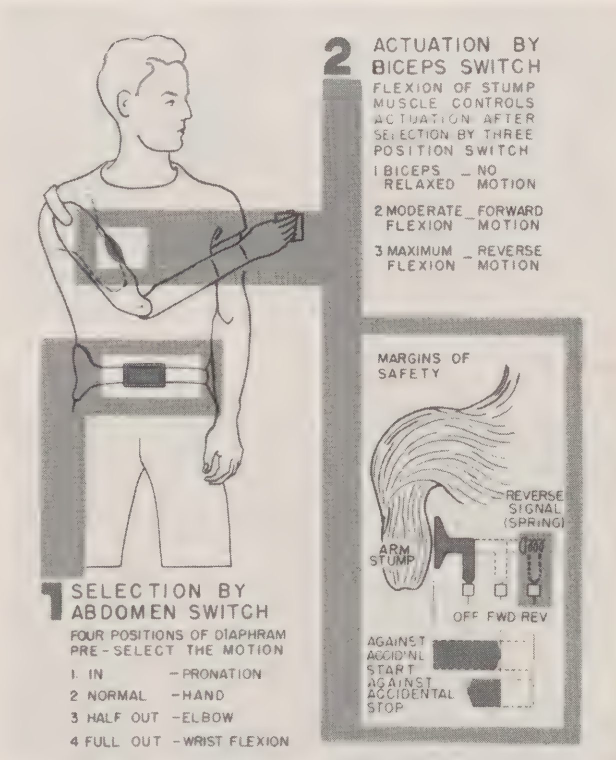


Fig. 70. Abdomen and biceps control for electrical arm.

(2) The Pneumatic Arm. Since a number of possible reservoirs for pneumatic energy were considered in the general analysis of arm power sources, it became necessary to estimate the pressure and volume of gas required for such a system. Considerable difficulty was experienced in designing completely airtight seals for the pneumatic cylinders which promised moderate efficiency. This precluded the use of "O" rings or similar seals and led to the investigation of rubber membranes which were inherently leak proof. One design permitted a rolling action of the rubber sac as shown in Fig. 71, but this proved to be unsatisfactory because at the minimum working pressure of sixty pounds per square inch the rubber sacs were forced out of the slots in the cylinder walls.

A rubber bellows mounted in a plastic tube, which served as a constraint and guide for the bellows action, also was tried. Here again, however, under moderate pressures the bellows expanded laterally and produced a binding action on the walls of the tube which could not be tolerated.

Although the problems faced in the cylinder and control experiments were difficult, they were not considered to be insuperable. However, further study and experiments indicated that satisfactory operation could not be achieved with pressures low enough for practical use and no further work was done on the development of a pneumatic system.

(3) The Hydraulic Arm. An obvious and distinct advantage of a hydraulic system is that hydraulic drives are independent of the path which must be taken by the connection tube because of, as is shown in Fig. 72, the inherent flexibility of a hydraulic transmission system. Although the general analysis previously had revealed the most promising of the available power sources, the crucial selection of the power and control sources could not be made until experimental models were built to test the various systems. Testing of these models pointed conclusively to the flexion of the ankle as the most suitable source of power and the most easily harnessed hydraulically. Studies then were initiated in tubing, fluids, valves, cylinders, packings, and controls, and by November, 1946, sufficient data had been compiled to permit the design of a system to operate and control a hand hydraulically.

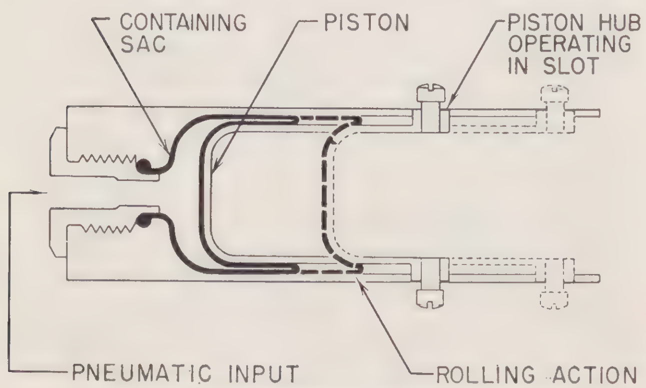


Fig. 71. Experimental rolling sac cylinder.

Fig. 72. Hydraulic transmission system showing inherent flexibility.

The tubing used in this system was a key factor governing the hydraulic design because it limited the working pressures which, in turn, determined the displacements of the system and the sizes of the actuators. Requirements established for such tubing included a bursting strength of sixteen hundred pounds per square inch, chemical inertness over a wide range of hydraulic fluids, alcohol, and body perspiration, a working temperature range from minus twenty degrees Fahrenheit to plus one hundred degrees Fahrenheit, and low expansion under

Fig. 73. Modified standard Miracle hand.

working pressures. A plastic tubing under the trade name "Saran" was selected.

Another difficult but important problem was the selection of suitable seals and packing for the hydraulic system which allowed a minimum of leakage and also a minimum of static and sliding friction. Aluminum cylinder walls were found to give the best frictional characteristics of any material studied and "O" rings were used for the seals. A comprehensive study of hydraulic fluids was considered to be of prime importance if high efficiencies were to be maintained. While commercial fluids were adequate in such factors as temperature characteristics, viscosity index, and inertness to the hydraulic components, high working efficiency was lacking. A mixture of ethyl or methyl alcohol and castor oil finally was determined to have the lowest sliding friction and a satisfactory viscosity index as well as other necessary requirements.

The design of proper valves for the control of the hydraulic arm also was important, since the selection of functions, locking, overload relief, and the walking disconnect were all performed by the valve units. Poppet type valves were used throughout the hydraulic system although leakage problems presented some difficulties until finally solved.

The first model to be built with the new hydraulic components was one in which only the grip was operated by ankle flexion, and particular stress was made on the problem of locking and unlocking the hand. A standard Miracle hand, as shown in Fig. 73, was used with an external cylinder and was closed by plantar flexion of the foot. The hand was opened by eversion of the ankle which operated a check valve. From this model knowledge and experience were gained which led to the reduction in size and weight of the foot and leg harness for the design of the second model. A metal shoe plate was designed in place of the external heel clamp and much of the control equipment was moved to a belt at the waist. The hand opening was controlled by a shoulder lift rather than ankle eversion, the latter often tripping accidentally.

In the design of the third model hydraulic arm, the leg mechanism was again reduced in size and weight and the external hand cylinder was mounted in the palm section of the Miracle hand. The field test model of the foot actuator, shown in Fig. 74, was light, simple, and proved to be satisfactory. The hand mechanism, shown in Fig. 75, was installed in the Miracle hand, and because of the removal of some of

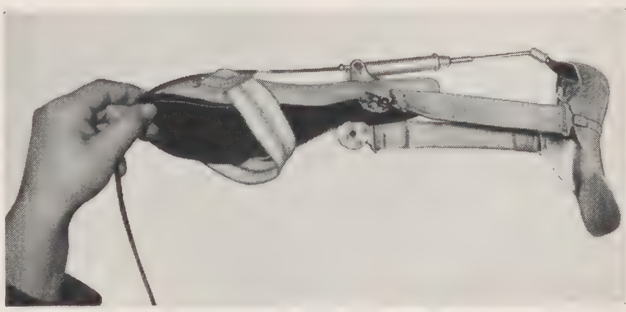


Fig. 74. Actuator mechanism attached to the foot.

Fig. 75. Hand mechanism installed in a Miracle hand.

the hand structure, the weight of the hand was decreased by 0.8 ounces. This model also was equipped with a pronation joint with a selector valve operated by a shoulder shrug to discriminate between the grasp action and pronation. The hand and mechanism, shown in Fig. 76, enabled the below-elbow amputee to grasp objects or pronate the hand at will.

Although some hydraulic arms were fitted to amputees, no valid basis for evaluation has been propounded as yet.

Fig. 76. Hydraulic hand mechanism.

(4) Development of the Hand. At the beginning of the project to develop a suitable artificial hand, it was considered proper to design and construct two completely different hands, one reflecting the point of view of the hydraulic mechanism, and the other with the electrical arm project in mind. It soon became evident, however, that the different designs of the two hands could not be resolved without obtaining actual data on the functional and cosmetic requirements of artificial hands. A hand function research, therefore, was inaugurated and carried on cooperatively between the UCLA project and the Bellevue laboratory to determine the most effective hand type; at the same time design work was conducted to produce satisfactory mechanical components.

The studies of the function of the hand showed that a fully articulated and equalized hand type had negligible advantages over the partially articulated type, and showed that a stable grasp was essential to a good hand design. It seemed then that the load-bearing fingers should not be articulated because they would not compare favorably with nonarticulated fingers in strength and stability. Since the minor group fingers were not actively engaged and since the functional studies had indicated that they should be designed to curl into the palm to form a shelf for objects held in a circular grasp as well as to remove them from interference with the grasp in other activities, these fingers were articulated.

The thumb design made possible a wide opening of the grasp and had two positions which could be selected readily by a simple bumping action on the thumb. The more flexed position permitted a grasp opening of one and five-eighths inches which was adequate for most objects; the extended position of the thumb allowed a total opening of three inches.

Probably the most important aspect of the hand design was the problem of securing maximum strength and wear resistance with a minimum of weight. After a variety of materials and a number of designs were studied, the properties of nylon, from a physical standpoint, proved to be superior to any of the other plastics investigated. Nylon manifested high flexural and impact strength as well as excellent resistance to chemicals and to temperatures up to four hundred degrees Fahrenheit. The principal difficulty in the use of nylon proved to be that of obtaining an inexpensive production process. A special process was developed by which injection molds could be made with Kirksite alloy at low cost.

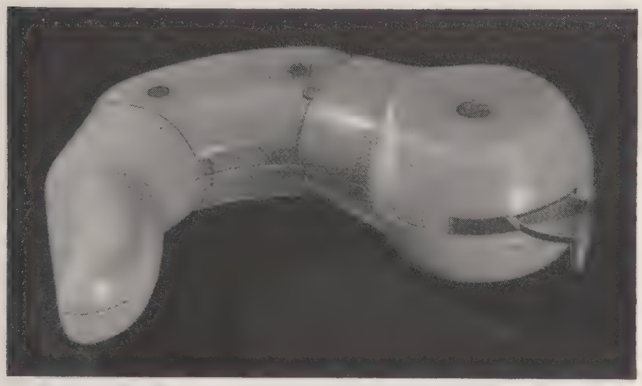


Fig. 77. Articulated nylon finger.

This led to a practical and inexpensive molding process for model or limited production work.

A decided advantage in using nylon was found in that it could be dyed readily so that a nylon hand used without a cosmetic glove for work purposes presented a moderately natural appearance. In Fig. 77, a nylon finger is shown in its flexed position. Note the smooth sealed joints which eliminated the necessity for a cosmetic glove and reduced the force necessary for compression and extension of the finger.

The hand structure itself was based on a magnesium casting which contained lugs for the wrist flexion, the finger, and the thumb bearings. It housed also the gearing in the hand, the force multiplier, and the various finger and thumb attachments. Palm contours were provided by a pair of molded nylon sections. Although the nylon hand has not yet been completed, enough nylon parts have been produced to give an indication that an unusually high strength-to-weight ratio has been obtained.

It was realized in the function studies of the hand that an abductible thumb would improve somewhat the performance of the artificial hand, but this was not included in this design in order to permit a sealed construction without the use of a cosmetic glove.

NORTHWESTERN UNIVERSITY

Evanston, Illinois

BACKGROUND. In December, 1945, work was undertaken at Northwestern University on a comprehensive survey of the available literature and patents on artificial limbs and on the design and construction of an accelerated leg testing machine. This subcontract was placed under the direction of Professor B. H. Jennings, Chairman, Department of Mechanical Engineering, and was headed by Mr. W. E. Dunshee, technical representative. Mr. J. F. Hopp aided in the design of test equipment and in the study of arm patents, and Mr. L. E. Barnes and Mr. W. S. Jones handled the testing program. Dr. Miklós Hetényi, Professor of Mechanical Engineering (and also a Member of the Committee on Artificial Limbs), gave helpful suggestions to this program.

PROJECTS. ***(1) Literature and Patent Review.***

(a) Artificial Legs. It was decided at the outset of this contract that immediate effort should be devoted to the literature and patent study and that the testing program should be left for future development. The study of the literature and patents dealing with artificial legs was the first to be undertaken. The basic plan was to segregate the individual mechanical features of each type of limb, classify these features according to design and principles of operation and, finally, to assemble the most outstanding and distinctive developments in report form. A preliminary study of artificial legs suggested that a general outline including structural elements, joints, methods of attachment to the body, and controls would cover adequately the significant aspects of artificial leg construction.

Perhaps the two most fruitful sources of material in this search were the United States patents and the German literature, although the prodigious amount of German literature, while especially valuable to the researcher because of the thoroughness with which the subject was pondered, was found somewhat disappointing because the main body of information was collected some twenty-five years ago. The exhaustive treatise, "Ersatzglieder und Arbeitshilfen," was examined systematically, as it was probably the most complete work available on this subject. English, French, and American literature provided some source material to a lesser degree, and an investigation of currently manufactured items completed this study. A report was prepared, using simplified drawings to illustrate the principles and including critical summaries in most cases, and was distributed to subcontractors and others interested in the design and construction of artificial legs.

(b) Arm Suspensions (Harnesses). Of immediate concern to subcontractors doing development work on the arm and hand was the important matter of suspensions. Toward this end a search of all available

patents and literature was made, and a report was prepared in which all harnesses having prominent points of merit were classified, sketched, and described.

(c) Artificial Hands. From the files available on artificial hands, a group of nineteen of the most significant examples was selected, a drawing was prepared for each of these hands, and a description of the mechanical operation was added. This material was assembled in report form which was then circulated to those working in this field.

(d) Hooks and Utility Devices. In addition to the three systematic investigations mentioned above attention was given, as the artificial limb program expanded, to the compilation of information on available samples of a "work arm" and the tools for use with such an arm. In a report entitled "A Summary of Representative Hooks and Utility Devices," twenty-three such appliances were sketched, classified, described, and evaluated. This material was assembled from United States patents, promotional material supplied by hook manufacturers, English and German literature, and current models of available hooks.

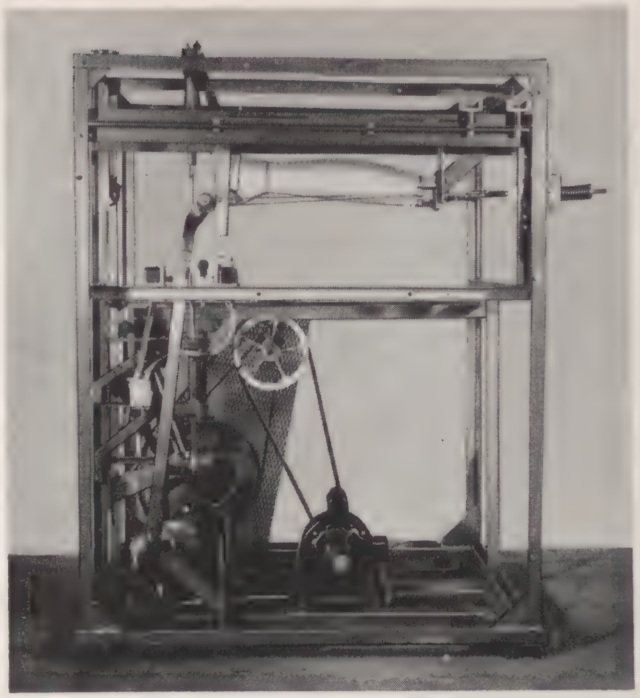


Fig. 78. Northwestern leg testing machine.

(2) Leg Testing Machine. In the design of the leg testing machine at Northwestern University, it was decided to avoid the complexity of a machine which would attempt to duplicate the normal walking cycle. It was assumed that the subjection of an artificial leg to the following three principal loads would be adequate:

(a) Compression loading of the instep and flexion of the toe section, with possible torsion about the longitudinal axis of the foot and about the vertical axis of the leg near the ankle,

(b) Compression loading at the heel, and

(c) Forcible extension of the knee joint while leg is subjected simultaneously to compression loading, lateral bending and torsion about the vertical axis.

The first load condition was met by a device which provided dorsal and toe flexion, while plantar flexion was produced by compressive loading at the heel. After considerable preliminary tests were conducted it was found that by permitting a roller to run from the toe to the heel, dorsal flexion and plantar flexion could be obtained in one test. The leg testing machine, shown in Fig. 78, combines plantar flexion and dorsal flexion with the incidental load on the shank and the knee. The third section of the test machine, which was to apply knee flexion, was not constructed because no above-knee legs were tested.

(3) Accelerated Wear Tests. Three shanks made of laminated Fiberglas cloth impregnated with a thermosetting resin and supplied by the United States Plywood Corporation were tested on this machine to determine the effectiveness of the joint between the plastic shank and the metal ankle block under conditions of repeated flexure using the loads of normal walking. In each test the shank was subjected to a minimum of three million cycles of repeated flexion, applying compressive end loading and repeated bending, observing especially the endurance of the bond between the ankle casting and the shank. In the first test shank the ankle and knee casting failed; in the second test shank no part of the leg failed during seven million cycles; in the third test shank there was a separation in the bond at the ankle block but no actual failure occurred in the leg. It may be concluded from these tests that the Fiberglas shank has sufficient fatigue life to withstand average service loading for a normal use period of at least three years. In Fig. 79, one of the plastic shanks with the test foot and the knee joint adapter is shown.

Fig. 79. Plastic shank with test foot and knee joint adapter.

NATIONAL RESEARCH AND MANUFACTURING COMPANY

San Diego, California

BACKGROUND. Because of the large background of experience in the field of development and fabrication of high-strength plastic parts, the National Research and Manufacturing Company was invited to participate in the program of research on artificial limbs. Specifically, its part in the program dealt with plastic materials and was divided into two main branches: a survey of the characteristics of available high-strength and low-pressure plastic laminates with emphasis on adaptability to the fabrication of artificial limbs, and second, the design of a lightweight artificial leg made of plastic materials and made as inexpensively as possible consistent with satisfactory service performance. This development program covered the period from February, 1946, through April, 1947.

The director of the National Research and Manufacturing Company, Dr. G. G. Havens, was helpful in guiding the project which was supervised efficiently by Mr. N. E. Handel, project engineer. Mr. G. A. Gordon was director of the survey of plastics, and Mr. E. P. Carmichael aided in the design and physical testing of component parts.

PROJECTS. ***(1) Investigation of Low Pressure Laminates.*** At the beginning of this project the use of laminated plastic materials in the manufacture of artificial arms and legs was limited because the cost of high pressure laminating techniques discouraged their use while the contact or low pressure laminating methods were of too recent an inception to have been used widely. It is true that fiber, usually in combination with wood and metal, had been used for some time and that "Cellastic," a napped cotton flannel impregnated with cellulose nitrate also had been used in this field. During the war, however, an entirely new type of resinous materials was developed which did not require such expensive equipment and since many of these resins became available on the market it seemed desirable to investigate the physical properties of various fillers which could be used in conjunction with this particular class of resins.

After a series of elimination tests was conducted, which involved the spot checking of each available resin with a standard filler for flexural strength, modulus of elasticity, specific gravity, air sensitivity, ease of handling, wetting characteristics, storage properties, and operating limitations such as curing times, temperatures, and pressures, it became possible to select eight resins which adequately represented the field. Each of these selected resins then in turn was impregnated into each of the available common fillers such as cotton muslin, paper, canvas, rayon, and Fiberglas in both woven cloths and mats. Some of the more recently developed fillers such as nylon, fortisan, and knit stockinette also were tried. Sheets eighteen inches by thirty-two inches were used because this size was estimated to be the minimum area from which the required test specimens could be cut. The number of sheets of cloth necessary to produce a finished laminate of approximately 0.125 inches in thickness was weighed and an estimate was made of the amount of resin required to give the desired filler-resin ratio. After impregnation, these flat sheets were cured at the particular pressure and temperature recommended for each resin, and bearing and tensile test specimens were cut from the sheets, filed to specific dimensions, and carefully sanded to remove file marks or other scratches which might have set up undesirable stress concentrations during the tests.

Tubes and compression specimens, shown in Fig. 80, were fabricated on a tube rolling device and cured as described above. These tubes were, of course, to be used as specimens for compression testing.

Physical tests were performed on thirty-eight resin-filler combinations (some combinations were not included because of obvious disadvantages) which included compression, tension, bearing, flexure, impact, weathering, flameability, and fatigue or resistance to repeated loading. These tests were performed by the University of California at Berkeley and additional data also were amassed to point out the fabricating qualities of each combination.

An analysis of all these tests indicated that there were only small differences in the properties of the resins tested. As a consequence, the selection of a resin for a specific purpose should be indicated by its cost, workability, stability, and similar factors, since the mechanical properties of these resins were found to be similar.

Fillers, on the other hand, proved to possess a much wider spread of physical properties. Fiberglas fabrics produced the highest strengths of laminates tested and had, in general, the best mechanical properties. However, the selection of a filler for use in the fabrication of any particular prosthesis should be determined by the shape and size of the desired part as well as existing specifications relative to strength-weight ratios. For example, knit stockinette fillers were found to be well suited for fabrication of odd shaped cylindrical objects which were not to be subjected to extremely high tensile or bearing stresses. Fortisan fabrics showed the highest strength of the organic type fillers, while nylon exhibited good tensile but poor compression and bearing strength characteristics indicating low inter-laminar adhesion. High tenacity rayon was considered suitable for use in fabricating parts requiring medium strength in combination with the lower specific gravities obtainable with organic type fillers. The basket type weave featured in this fabric was found to be satisfactory for forming surfaces having compound curvatures. In general, fabricating and curing techniques seemed flexible enough to be adaptable to facilities and equipment either in small shops or in larger manufacturing plants.

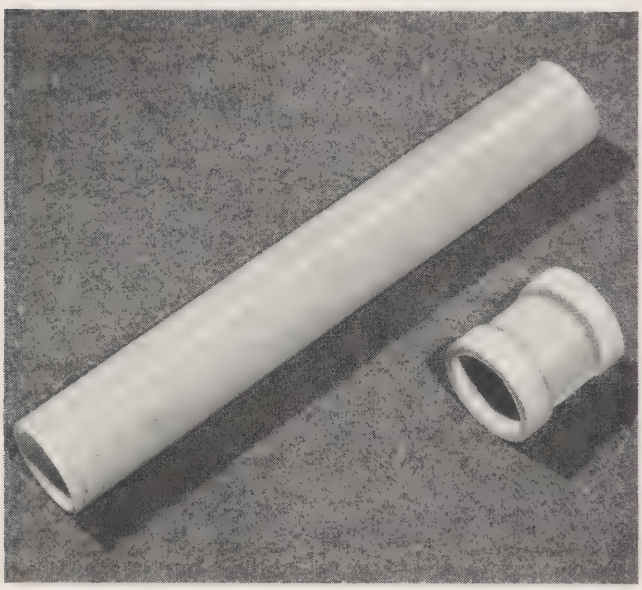


Fig. 80. Tube and compression specimen.

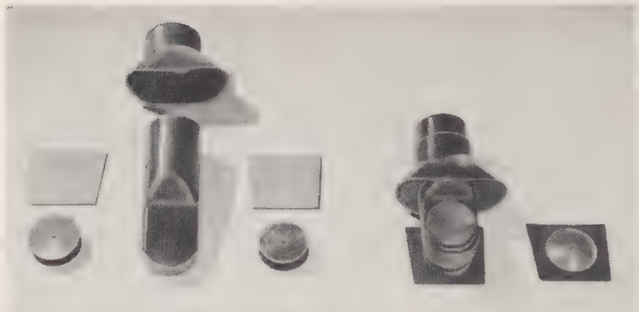


Fig. 81. Ankle joint components and assembly.

(2) Design of an Artificial Ankle and Foot. When this phase of the project was started very few quantitative data were available to designers of artificial ankles and feet. It was necessary, therefore, to analyze the mechanical functions required before attempting to formulate a design that would adequately simulate the motions of natural walking.

It was decided early in this project that the entire mechanism of the ankle joint should be characterized by simplicity, lightness, and durability. It should be capable of plantar flexion as well as dorsiflexion and of some lateral motion. It was believed possible to incorporate these motions in the ankle joint and still maintain the required stability through the use of rubber bushings. After considerable stress analysis and some laboratory tests, an ankle joint was designed and constructed consisting of two conically-faced rubber sandwich bushings, both having a common axis of rotation and each mounted parallel to a vertical plane passing through the geometric center

of the foot. These bushings with other ankle joint components are shown in Fig. 81, along with an assembled ankle joint. To facilitate attachment of the rubber bushings to the deflecting member and also to the foot, it was necessary to bond metallic (aluminum) cones to the rubber bushing faces. This involved the selection of an adhesive which possessed shear strength equal to or greater than the rubber element. A material called Metlbond, manufactured by this subcontractor, was selected because of its high shear strength characteristics.

The ankle bushings, when in normal operation, were, of course, subjected to some static load but repeated rotational shear and impact produced at the time of bumper contact were predominant. To test these bearings, a dynamic testing machine, shown in Fig. 82, was constructed which subjected the experimental bushings to pure rotational shear. Although tests had not been completed at the time of the writing of this report, two pairs of bushings had completed satisfactorily over six million cycles. The ankle joint, complete with attachment, weighs approximately eight ounces, embodies simplicity of mechanical design, and is readily replaceable.

After considerable investigation, an artificial foot was designed and constructed using balsa wood as the basic material and covering the wood with Conolon, a Fiberglas cloth impregnated with a particular modified resin. The foot core assembly with the ankle assembly in place is shown in Fig. 83 before shaping.

In designing the toe hinge it was necessary to provide a resilient member which would withstand repeated flexing without breakdown and yet furnish the resistance to bending necessary to insure a natural walk. Tests of various types of constructions demonstrated the practicability of sandwich type hinges consisting of a rubber core bonded by Conolon skins. These hinges were extended and bonded over the entire length of the foot to avoid failure of the balsa wood in horizontal shear.

Experiments have demonstrated that the assembly of this artificial foot of balsa wood covered with a resin impregnated Fiberglas cloth and with the rubber sandwich bonded ankle joint is light in weight, durable, and offers sufficient resistance to moisture. The general design lends itself to mass production with consequent low unit costs.

(3) The Artificial Shin and Knee. Here again, the investigation was pointed toward a well functioning prosthesis, and yet one which would be simple in design and construction. The requirements for an artificial shin were found to be satisfied most simply by the use of a single column as the main member, covered with plastic fairing to lend shape to the leg. Based on theoretical calculations backed up by laboratory tests a shin column was constructed having solid walls built up of Fiberglas cloth fillers and an outside diameter of 1.709 inches.

Covering or fairing material for the shin must be light in weight, easily workable, like the normal

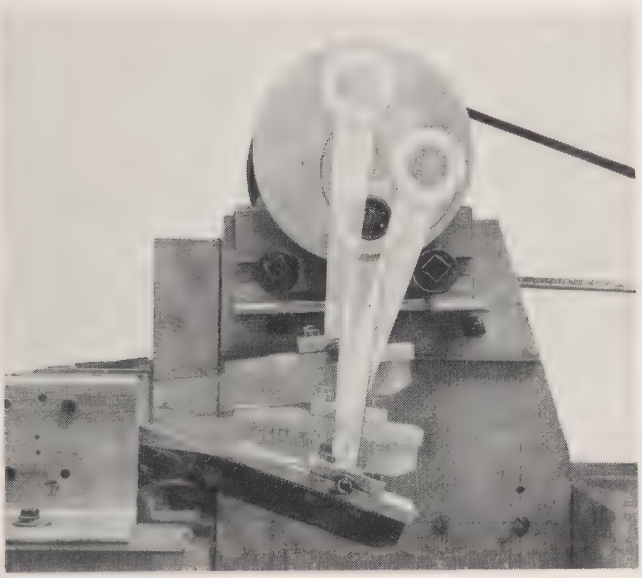


Fig. 82. Dynamic testing machine for ankle bearings.

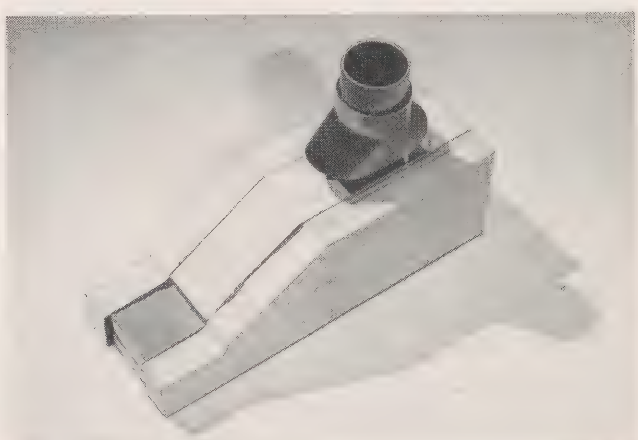


Fig. 83. Foot core assembly with side blocks and ankle assembly attached.

skin, and have a reasonably high impact resistance. A workable but not completely adequate covering was constructed with the use of cellular cellulose acetate as a basic fairing material because of its light weight and workability. Covering this material with Conolon gave the necessary impact resistance, but unfortunately formed a hard surface. This surface was in turn covered by a thin layer of sponge rubber and the whole encased in a vinyl skin completely covering the shin member. A flesh color paint was applied to the under surface of this skin, rendering it resistant to discoloration and giving it the translucent appearance of flesh. Because of the inability to secure cellular cellulose acetate in the necessary size, this process of fabricating the covering would not be efficient if present methods were used.

Applying data obtained from investigations of the mechanics of normal walking, a knee was designed which embodied: (a) a positive lock when the shin was placed in the fully extended position; (b) a restoring torque at the knee joint capable of returning the shin to the extended position after the knee had been flexed; (c) a cushioning action at the knee when the load was applied. This design, as shown in Fig. 84 in its unloaded position, consists of a "V" groove, semi-yielding wedge type brake mechanism supported by dual conical rubber sandwich bushings similar to those used in the ankle joint. In its unloaded position, there is ample clearance between the rubber wedge and the "V," thereby permitting free action of the knee. When load is applied, as shown in Fig. 85, the rubber wedge comes in contact with the "V" groove resulting in considerable fractional holding force. This design afforded a positive lock through at least 2.7 degrees of inclination with the vertical, beyond which some slippage occurred; the frictional drag, however, was of such a magnitude as to prevent a rapid collapse of the knee.

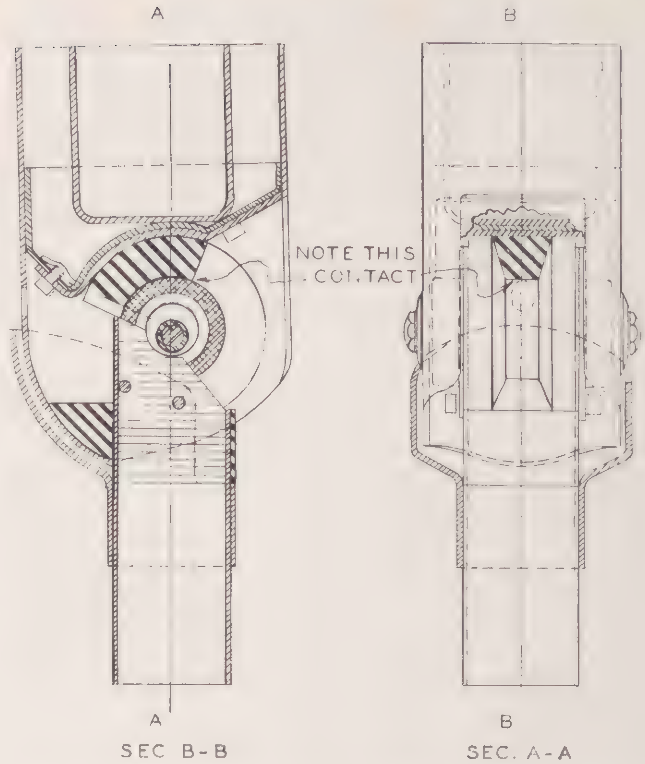


Fig. 85. "V" groove rubber wedge-type knee in loaded position.

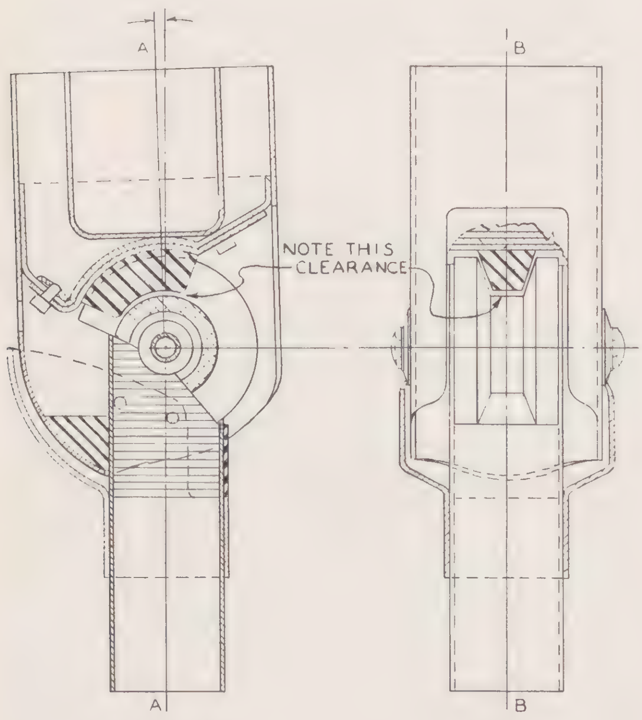


Fig. 84. "V" groove rubber wedge-type knee in unloaded position.

(4) Design and Construction of Suction Sockets. *(a) Below-knee Suction Sockets.* Some work was done in fabricating a below-knee suction socket out of stockinette cloth impregnated with Selectron Resin No. 5003. While there was some indication that the socket would remain on the stump during walking and that the vacuum principle might be employed, the lack of background of practical and medical experience of this subcontractor was among the factors which prevented the fitting of a statisfactory and comfortable below-knee socket. As yet, the applica-

tion of suction sockets to below-knee amputees is not successful.

(b) Above-knee Suction Sockets. In studying various designs of sockets for above-knee amputations, the possibility of producing one capable of standard fitting was believed to be worthy of consideration.

In examining the basic requirements for a standard suction socket it was noticed that the stability and enveloping requirements were similar to those encountered in the design of an automobile tire carcass and suggested this type of construction. In Fig. 86, the details of construction of this standard fitting socket are shown. It is the opinion of this subcontractor that further development on a socket of this design might possibly standardize the fitting of above-knee stump sockets.

(5) Production Survey. This survey was made to determine the cost of manufacturing plastic artificial legs. The data were obtained from experimental fabrication methods to determine the amounts of time and materials necessary to construct each component part. Allowances were made for savings that would occur in fabricating moderately large production quantities. The survey included an estimate of the capital required to set up and operate a plant to produce eight artificial legs each day. The final cost figures, which are not given here because of the complexity of factors involved, are thought to be reasonably accurate estimates of production costs of the finished legs under present economic conditions.

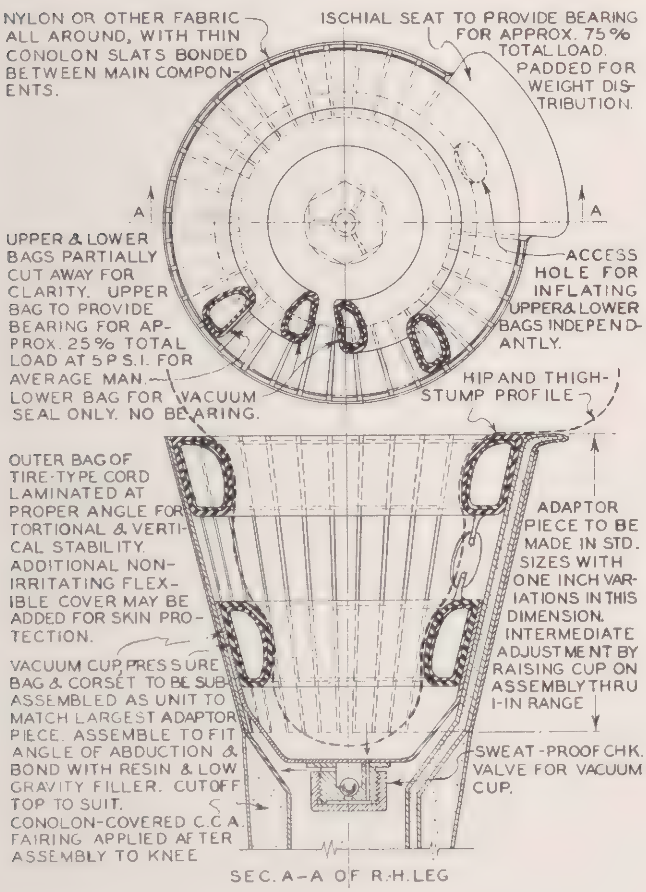


Fig. 86. Above-knee suction socket.

A. J. HOSMER CORPORATION

Los Angeles, California

BACKGROUND. At the beginning of the second world war the A. J. Hosmer Corporation was formed to develop and manufacture prosthetic appliances needed by the United States military services. Because of this interest, an invitation was extended to Mr. Karl C. Vesper, President of the A. J. Hosmer Corporation, to represent his company at the Committee's symposium held in Chicago in January, 1946. As a result of this meeting this corporation was invited to participate in the Committee's program by developing a knee disarticulation weight-bearing leg with a knee lock. Work was started in March of 1946, and shortly thereafter the project was enlarged to include also the development of a work arm, interchangeable working tools, and a hydraulic arm control. Work on these projects under the Committee's auspices was stopped in June, 1947, but it is hoped that this company will continue its research and development program and will become a permanent and valuable addition to the artificial limb industry.

PROJECTS. ***(1) Knee-bearing Legs Equipped With Knee Locks.*** The principal consideration in designing a knee lock for knee disarticulation amputations, or knee-bearing stumps, is the development of a practical mechanism which will lock or apply a braking action to the artificial knee under conditions of involuntary knee flexion. Because the knee space in this leg is occupied by the disarticulation stump, the design problem is complicated by the necessity of finding other locations in which to place the knee lock.

Although both a hydraulic system and a mechanical friction system of locking and braking were considered, a comparison of the two systems early in this program established the development of the hydraulic system as being the more feasible.

After the decision had been made to design a leg with a hydraulic knee lock, the first step in the investigation was the construction of a mock-up of a hydraulic system, shown in Fig. 87, which duplicated the essential functions of the normal leg but was in no sense a finished model. This model was constructed crudely of plywood using war surplus hydraulic parts in constructing the brake unit. The two slave cylinders in the foot, one of which was in the heel and was actuated when weight was applied to the heel and the other was in the ball of the foot and was actuated by flexion of the toe piece, served to actuate a third hydraulic cylinder which in turn closed the valve in the brake cylinder blocking the flow of fluid and thus stopping knee flexion. From a study of this original mock-up unit, sufficient knowledge was gained to undertake the development of the first model of a hydraulic weight-bearing knee lock.

As a preliminary measure of precaution leading to success in the final design, considerable investigation was made on the component parts comprising the hydraulic braking and locking unit. Cylinders were cast and machined out of various materials, characteristics of various types of hydraulic valves were studied, seals for pistons, piston rods, and valve units were evaluated, and methods for suspending the braking unit and connecting it to the thigh piece were examined systematically. For use on the experimental legs, redesigned hinge straps, shown in Fig. 88, were constructed of 4130 steel normalized to permit ready bending to conform to the thigh and shin shapes. Sealed ball bearings were press-fitted as a unit into the strap socket.

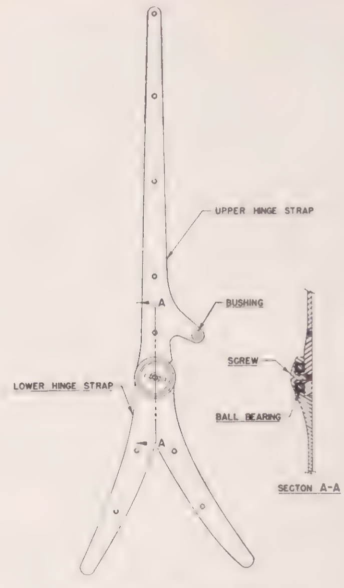


Fig. 88. Knee hinge.

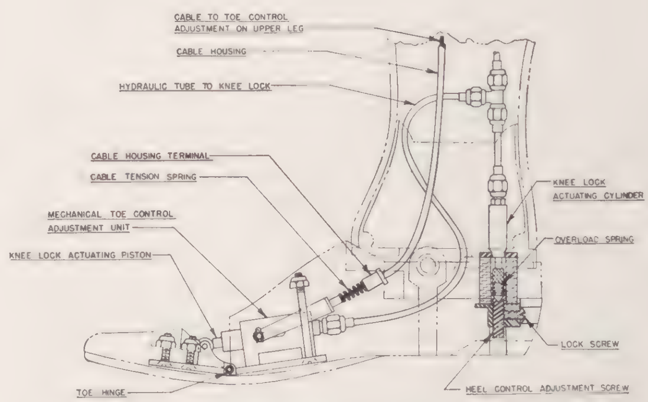


Fig. 89. Foot assembly with toe hinge and mechanical control adjustment unit.

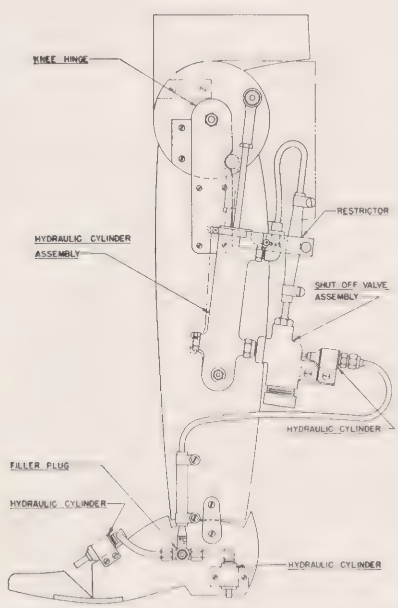


Fig. 87. Original mock-up of hydraulic knee lock.

Several different foot controlled mechanisms were built to actuate the hydraulic knee lock. Rubber bulbs first were placed in the toe and heel to actuate the hydraulic knee lock control valve. Then an electrical method, using heel and toe contact switches, was tried. A completely mechanical foot assembly also was built, on which flexing of the toe or indenting of the heel actuated a push-rod attached to the knee

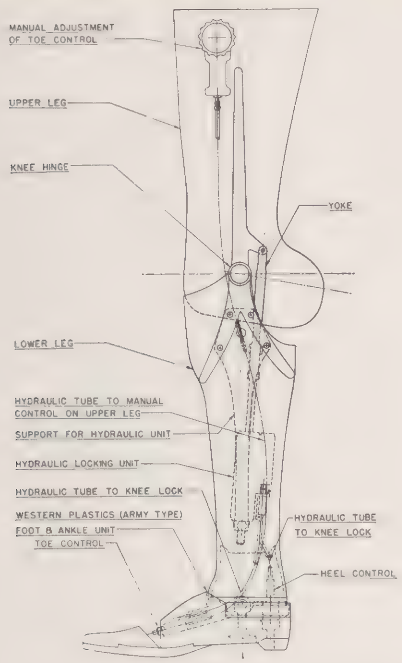


Fig. 90. A hydraulically controlled leg.

lock. The final foot assembly, shown in Fig. 89, included the addition of a metal hinge connecting the toe to the foot which improved the stability considerably. Selection of the position of toe flexion locking was accomplished by means of a hip-mounted control, regulated by a rotating knob.

After the design and construction of the component parts had been completed, six leg models were built successively, each an improvement on the preceding one and each incorporating some new developments coming as a result of continual testing. In Fig. 90, the final design of a completely hydraulic control leg is illustrated schematically. Although service tests have not been completed on this model, there is indication that it will take an important part in the field of artificial legs.

(2) Work Arms and Tools. The basic research in the field of work arms and tools which was done by the A. J. Hosmer Corporation during the recent war, provided a good foundation upon which to conduct the development work of this project. The purpose was to develop arms and tools of sufficient strength and durability to be used safely in all vocations.

The first consideration in this project was pointed toward the development of a provisional arm, Fig. 91, to which was attached a quick-change wrist. This arm was used for conditioning new stumps, and consisted of a shell or frame containing a flexible stump sheath which could be adjusted to any size or shape of the stump. The quick-change wrist permitted attachment of many kinds of tools and training devices to aid in improving the muscular system while the stump was in the process of healing. This provisional arm later was improved by constructing it of laminated Fiberglas cloth with inside and outside coverings of stockinette plastically bonded.

The satisfactory operation of the completed work arm depended, of course, on the improved efficiency and increased sturdiness of the basic parts. The control cord, illustrated schematically on a below-elbow work arm in Fig. 92, was constructed of a pre-formed stainless steel aircraft cable housed in a conventional stainless steel coil sheath. The housing button rotated freely in the housing terminal and adapted itself to the direction of the cable pull. A quick connector

Fig. 91. A provisional arm with quick-change wrist.

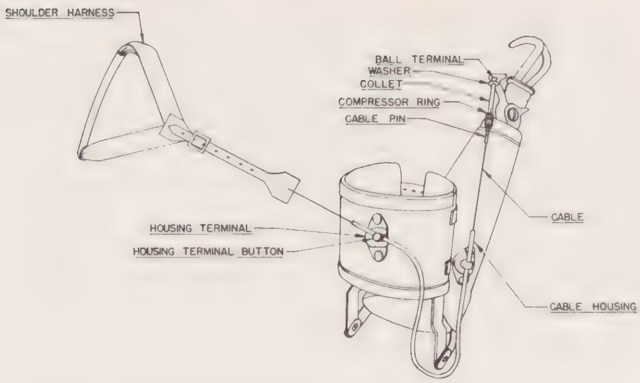


Fig. 92. Cable control for below-elbow work arm.

Fig. 93. Improved quick-change wrist.

and extensor was developed also for the cable to provide a rapid-change method of attaching it to hands and hooks and for lengthening or shortening the cable when a different hand, hook, or other tool required a different length of cable. This quick-disconnect attachment weighed one-half ounce and withstood a force of one hundred pounds.

An improved quick-change wrist, Fig. 93, incorporates the features of allowing free rotation of the inserted tool as well as a braking mechanism to control the degree of rotational friction desired. It also permits the locking of the hook or hand against rotation. These units have been designed so that they may be used with plastic, metal, wood, or fiber forearms and have been proved satisfactory in service tests on amputees.

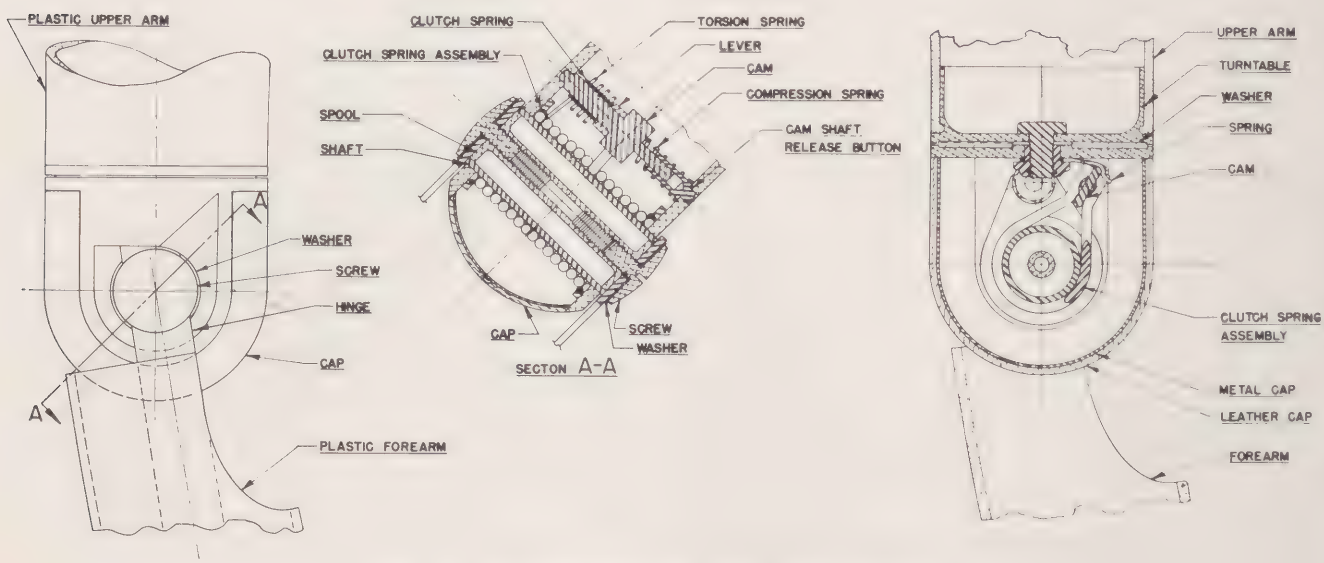


Fig. 94. Doubly-wrapped coil spring clutch assembly.

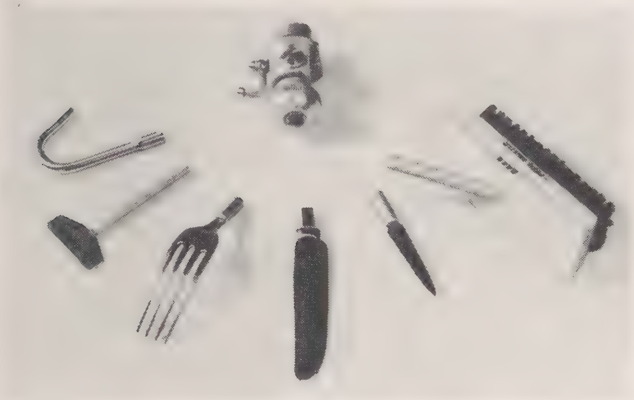


Fig. 95. Tool holder and accessories.

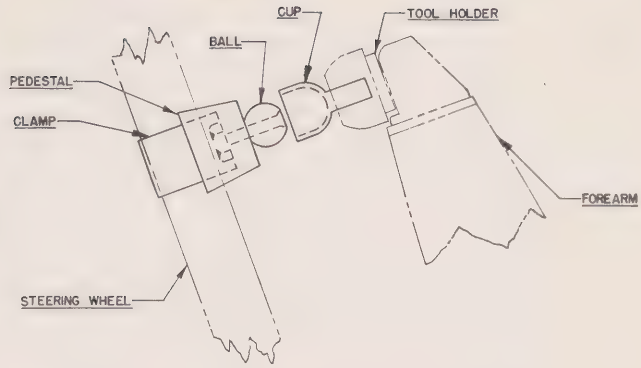


Fig. 96. Ball type steering wheel attachment.

An important development for the above-elbow work arm was the design and construction of an elbow unit, Fig. 94, which consisted of a doubly-wrapped coil spring clutch employing a manually operated cam to release the clutch voluntarily. A force of three pounds was required to operate this control cam while the elbow mechanism has withstood a fifty pound load on the end of an eighteen inch forearm without slipping. Because of its simple design and because of the few moving parts and the relatively small amount of motion of each, this elbow locking mechanism has shown promise as an inexpensive and lightweight solution for the above-elbow working arm.

The tool holder, illustrated in Fig. 95 with several of the easily inserted attachments, permitted locked flexure, as well as locked pronation and supination positions. It held any tool or device, which was mounted on a 5/16 inch shaft, by means of a simple collet chuck. A ball type steering wheel attachment, illustrated schematically in Fig. 96, is used in conjunction with the tool holder. This device has been tested by several amputees who have attested to its usefulness. A farm utility tool, Fig. 97, provided an attachment for such activities as pitching hay or shoveling, which allowed a universal motion action at the wrist junction and assumed that the normal hand is used as a driving force for each attached implement.

A flexion, pronation, and supination position mounting for hooks, illustrated in Fig. 98, was constructed particularly for the use of bilateral amputees. Although each position has to be set manually, it can be done by a bilateral amputee. A most practical use of this turret attachment has been in the undertaking of heavy work by amputees.

Fig. 97. Farm utility tool.

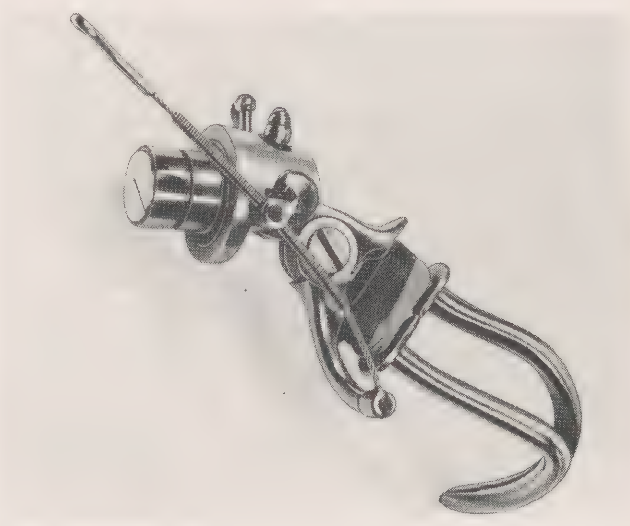


Fig. 98. Turret hook mechanism showing wrist flexion.

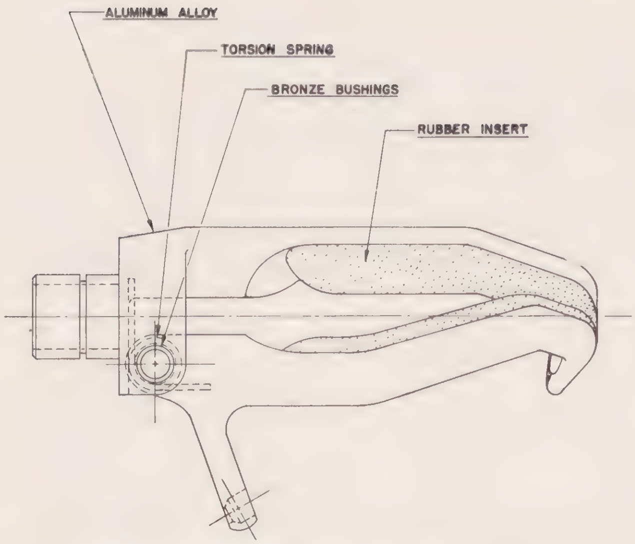


Fig. 99. Utility hook with rubber inserts.

Work on an improved utility hook design, Fig. 99, progressed to the point of changing the conventional hard inner surfaces of the hook prongs by bonding them with rubber and by changing the shape of the prongs somewhat. The conventional rubber bands used to close the hook were replaced by a torsion spring. Limited tests made thus far by amputees have indicated a feeling of improved utility by the use of this hook.

C. C. BRADLEY & SON, INCORPORATED CATRANIS, INCORPORATED

Syracuse, New York

BACKGROUND. The research work conducted under this project developed from two sources: the interest of Mr. William J. During, Executive Vice-president of C. C. Bradley & Son, Incorporated, in an attempt of the die-casting industry to meet the structural requirements for artificial limbs, and the preliminary studies made by Mr. John G. Catranis, President of Catranis, Incorporated, on artificial limbs. This interest and these investigations resulted in discussions among Members of the Committee, Mr. During, and Mr. Catranis, and finally culminated in the negotiation of a contract between C. C. Bradley & Son, Incorporated and the National Academy of Sciences; Catranis, Incorporated became a subcontractor under C. C. Bradley & Son. Work began in March, 1946, with its aims and objectives the study of the foot, ankle, and knee action, and the construction and design of an improved lower extremity prosthesis.

PROJECTS. ***(1) Mechanical Knee Locks.*** As has been pointed out previously in this report, studies of human gait at the University of California established the fact that the normal knee locks in two separate positions during each complete walking cycle. The knee is locked as the heel strikes the ground, flexes slightly to cushion the shock of impact, and, as the body rides over, the knee extends until it assumes the second locked position. In order to simulate the normal gait with a prosthesis, it seemed desirable that the knee locking device should permit a small amount of initial flexion upon application of weight at heel impact, and as the body rides over the prosthesis, extend the knee and lock again at the push-off phase.

There were three primary objectives in this study of mechanical knee locks: the design of a knee lock which would be actuated on application of the load; the provision of a limited amount of knee flexion upon application of load; allowable knee extension when in the locked position.

The first model of the mechanical knee lock contained a free-wheeling mechanism and although it was demonstrated that the knee locked satisfactorily at any point during flexion, the leg would not extend until the load applied was removed, since the torque required to extend the leg was practically the same value as the torque applied by the load. A subject wearing the first mechanical knee lock is shown in Fig. 100, walking down a ramp.

After tests were conducted and observations evaluated on this first mechanical knee lock a second model was made and tested. Observations on the various tests conducted on both models of the mechanical prostheses indicated the following: (a) a mechanical knee-locking device had been designed which locked at any angle when a load was applied; (b) a limited amount of rotation, depending on the load applied, occurred about the knee axis which was due to the shock absorbing characteristics of the knee-locking device; (c) the knee lock permitted extension of the knee with the mechanism in a locked position, although the mechanism would not extend until the rotation which occurred during shock absorption allowed the return of the rollers to normal starting position; (d) the force required to operate the locking device was considerably less than the

weight of the prosthesis; (e) mechanical knee locks permitted slow and fast walking, ascending and descending inclines, and recovery from fall upon application of load. It did not, however, permit sitting down or descending stairs when the load was applied.

Studies on this project have indicated that it is quite improbable that a suitable mechanical knee lock could be devised to provide all of the features required in a controlled flexion type of mechanism. As yet, the problems of high-shock, stress, and wear characteristics inherent in a mechanical knee lock have prevented the development of a satisfactory mechanical device because of the strength-weight ratios of materials available. In view of the above difficulties, work on mechanical knee locks was discontinued by this subcontractor and all further studies were conducted on the application of hydraulic type systems as outlined below.

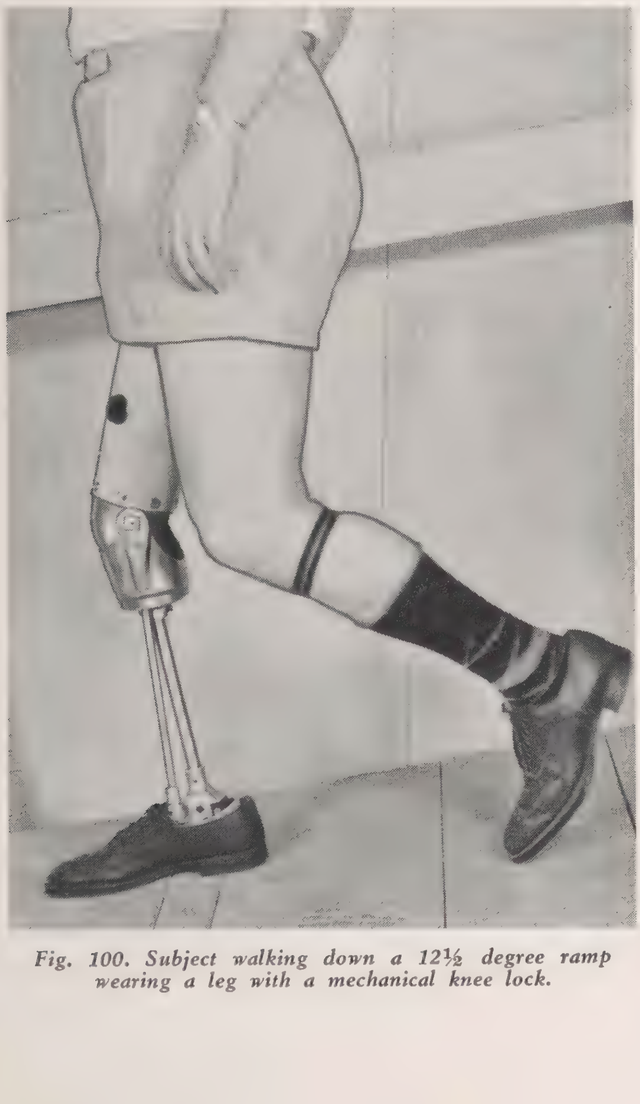


Fig. 100. Subject walking down a 12½ degree ramp wearing a leg with a mechanical knee lock.

(2) Hydraulic Knee Locks. From the work conducted on the mechanical type knee lock and from additional studies, criteria for a hydraulic device were established which provided an attempt to substitute partially for the missing muscular functions. A hydraulic device should contain a throttling valve for controlling the rate of knee flexion and should provide a full lock at any point of knee flexion as and when desired. It must contain a check valve to permit reversing the fluid flow providing free extension of the lower limb, and a relief valve should be included for over-riding the throttling valve for high-shock or torque loads. Suitable shock absorbing stops for full extension or maximum flexion are desirable as well as an energy accumulator for absorbing shock of knee flexion when fully locked to provide return of energy to the system.

The association of studies for mechanical knee locks led to a preliminary design coupling both mechanical and hydraulic features. This lock was operated by means of a bellows type differential control and its braking action was provided by a conventional type brake-band operated hydraulically, the band being on the outer race of a free-wheeling device. The free-wheeling device was constructed to permit the outer race to rotate in only one direction and allowed the brake to take effect only when there was a load applied on the prosthesis.

Although this device presented a possibility for gradual deceleration before locking, the system seemed impractical because of the high working pressures and frequent adjustments required by the brake. Calculations revealed that the magnitudes of torques necessary for control, even for normal functions, would not permit a practical device of this design within the space limitations. Further work on this knee lock, therefore, was discontinued.

The next step led to the development of a completely hydraulic knee lock. This device contained a hydraulic cylinder mounted in the shank and was designed to absorb the shock of heel impact allowing initial knee flexion. A diaphragm in the bottom of the stump socket was intended to act as a control for walking, but a foot control was used for sitting down and descending stairs. Further observations on this knee lock pointed out that the pressure differential in the suction socket used to actuate the control valve in walking was a duplication of the functions for unlocking this valve since lateral motion of the foot which occurred during walking provided the same action. In sitting down, for example, the am-

putee could spread his legs slightly, shift his weight toward the normal leg, and thus obtain a sufficient amount of lateral motion to actuate the throttling valve, which in turn controlled knee flexion. It seemed obvious, therefore, that if this foot action would provide release of the knee lock, the differential pressure suction socket control would be unnecessary. The next step then was a redesign fully utilizing foot control.

This redesigned knee lock was the first hydraulic model in which the action depended neither upon the weight of the subject nor upon pressure differential in the suction socket to lock the knee.

In Fig. 101, a diagram of this lock is shown. It consisted of a hydraulic cylinder, D, and piston, one end of the piston shaft, C, being connected to a lever, B, which in turn was connected directly to the socket, A. The piston shaft extended through both cylinder caps and a hydraulic line connected to both top and bottom cylinder caps contained a check valve, F, which permitted free extension. In the same line a throttling valve, E, was operated by means of a lever connected by a cable, G, to the plantar plate of the metatarsus section of the foot, actuation of which permitted fluid to by-pass the check valve and provided flexion of the knee. The control valve also contained a spring checking feature which permitted the valve to open slightly which allowed flexion to occur under a shock load.

While this model demonstrated the principles of operation of the foot control, observations of tests disclosed that the foot control lagged in operation and did not permit the knee to flex soon enough during the start of the oscillating or walking cycle. It was decided subsequently to substitute a different means of controlling the check valve. This new control consisted of a small bellows attached to the top of the stump socket and actuated by the muscles of the stump. This method of control is described in detail below. Results of functional tests of normal walking, descending stairs and a ladder, and recovery from a fall, demonstrated that the control was sensitive enough through the muscle action to actuate the locking or throttling mechanism.

Because of some structural considerations coming as a result of a stress analysis, and because of the desirability, shown in functional tests, of separating the valve functions such as the relief, throttle, and check valve, this hydraulic model was modified somewhat to incorporate separate throttle, relief, and check valves which more accurately controlled the rate of descent either when sitting down or walking down stairs. This new model (No. 6) used a bellows muscle control on the socket for operating the check valve and also a foot control for operating the throttle valve. This leg also included a newly designed strut construction which provided a wider latitude for structural considerations, and permitted the leg to be covered more easily with a natural flesh-like material.

It has been recommended that this last hydraulic mechanism be modified somewhat by the inclusion of the combination valve design of the previous leg, and that several models be completed and service tested to determine the operation of this device.

(3) Suction Sockets and Suction Socket Controls. Although the program of this subcontractor was concerned principally with the development of knee locks, shanks, and artificial foot and ankle construction, it became necessary to devote a portion of the efforts to the design and application of a suction socket in order to utilize the pressure differential created in the suction socket between the oscillating cycle and the heel contact phase for a controlling device. It seemed expedient to examine systematically the shapes, fitting, and fabricating methods available and to design valves which would control a safe, low negative pressure in the socket as well as allow the expulsion of air in order that a constant supply of fresh air would be available in the stump area.

Experiments were conducted on two types of suction sockets: one for controlling knee locking mechanisms by means of differential pressures in the socket which actuated a diaphragm control at the distal end of the socket; the other type following the conventional suction socket shape as described elsewhere in this report.

A design of the latter type is illustrated in Fig. 102, by showing sectional views at different levels of the stump, and compares the stump contour outlines with muscles relaxed to the shape of the finished socket. This socket provided an accurate fit which subsequently was proved to be important through tests which applied various weights to the leg to determine the magnitude of forces necessary to remove the leg from the stump for various combinations of negative differential pressure and stump shapes.

Experiments on the first type of suction socket indicated that the differential pressure type of con-

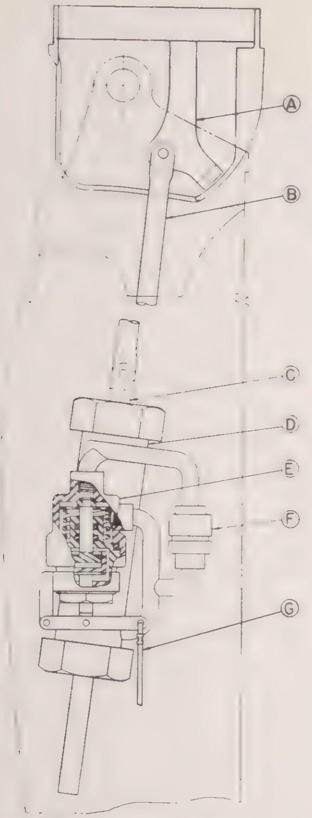


Fig. 101. Schematic diagram of a hydraulic knee lock made by Catranis, Incorporated.

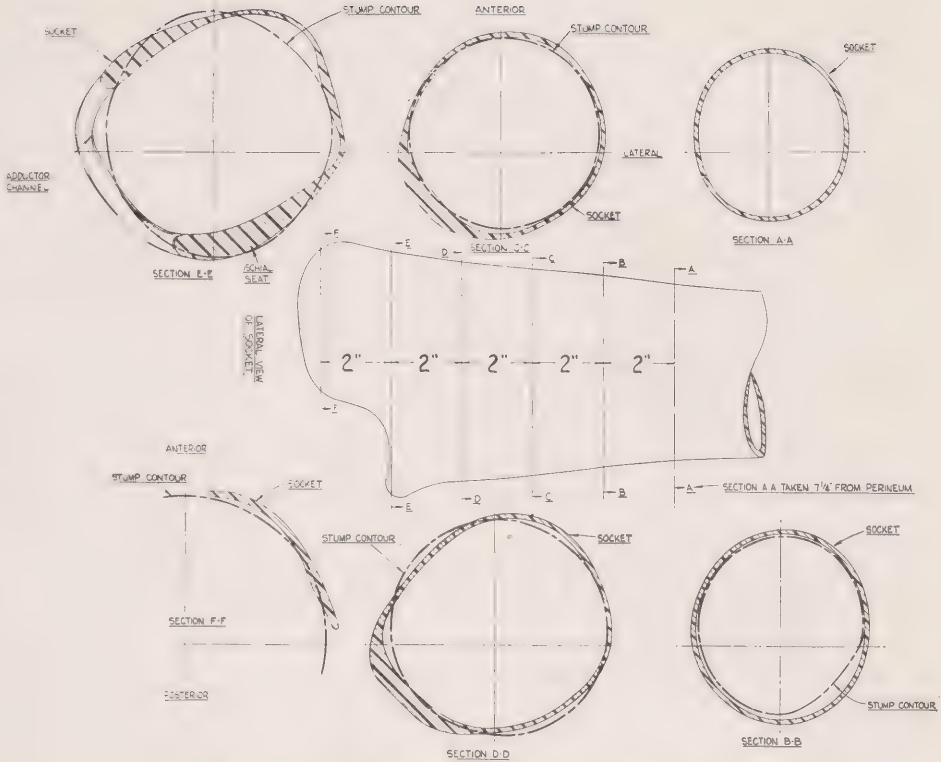
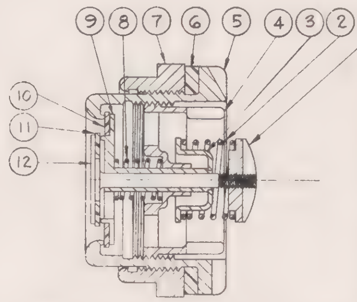


Fig. 102. Sectional views comparing a finished suction socket with contours of the stump with muscles relaxed.



Nº	DESCRIPTION
1	ADJUSTING NUT
2	INLET VALVE SPRING
3	SPRING SUPPORT
4	ADJUSTING SCREW
5	BODY
6	GASKET
7	SOCKET INSERT
8	EXHAUST VALVE SPRING
9	EXHAUST VALVE
10	EXHAUST VALVE DISC
11	INLET VALVE DISC
12	INLET VALVE

Fig. 103. Suction socket stocking plug with inlet and exhaust valves.

trols was not satisfactory and did not meet the functional requirements necessary because its operating cycle did not duplicate the normal cycle of the various muscles controlling a normal leg. This finding resulted in discontinuation of research on differential pressure type controls for the knee-locking mechanism.

After a considerable amount of experimentation with the various types of suction socket fits, a valve was designed which combined an intake and exhaust for the flow of air and provided an opening for the removal of the stump sock after the leg first had been put on. This valve, shown in Fig. 103, allowed the negative and positive pressures within the socket to be controlled accurately and provided for air displacement; the rate at which air was displaced depended upon the valve setting and upon the rate at which the amputee walked.

(4) Knee Lock Controls. As a practical approach to the control of the hydraulic knee lock, the pressure available from muscle groups which operated in phase with the normal walking cycle was harnessed. This control utilized the change in relative positions between the stump and socket which occurred because of contraction of the stump muscles, and preliminary tests conducted on hydraulic type prostheses indicated satisfactory operations for normal walking, descending stairs, ascending and descending inclines, sitting down, and functions such as stepping off a curb or recovering from a fall.

A sketch of two phases of the walking cycle, Fig. 104, illustrates the muscle action at the time of heel impact and at the end of the walking cycle with the toe push-off. On heel impact, this ischial-quadriceps knee lock control was actuated by the normal tensing of the leg muscles which exerted a maximum pressure on the pad as shown. At the end of the walking cycle, pressure was released by the normal relaxation of the leg muscles, and the knee was unlocked automatically.

Several types of controls were tried. The original control, Fig. 105, consisted of a rubber bulb filled with water and was fastened to the top of the suction socket in the front. As the body pressed forward to the front of the socket, the bulb was squeezed, thereby forcing the liquid out and actuating the knee lock.

Because this rubber bulb control did not supply enough force to actuate some of the hydraulic valves, a sylphon type bellows control, shown in Fig. 106, was tried on one hydraulic leg. Observations during walking tests using this control demonstrated that the location and position of the control pad was particularly significant since the available pressures varied considerably with slight changes in the positioning of the pad. A lever-type control, Fig. 107, then was designed to overcome the disadvantage of the bellows-type that it could not remain in contact against the thigh during the entire walking cycle. With some modification this latter control was installed on all amputee models and was identical in design for both mechanical and hydraulic legs.

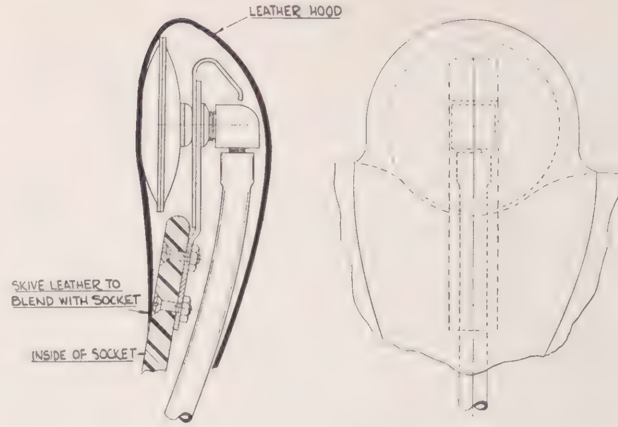


Fig. 105. Hydraulic-bulb type ischial-quadriceps control for mechanical knee locks.

(5) Toe Pick-up and Shank Construction. One of the difficult problems involved in leg construction was the arrangement of a toe pick-up mechanism which provided clearance between the walking surface and the toe during the swing phase of the walking cycle. Ideally this mechanism should permit the necessary clearance between the toe and the walking surface either for normal walk or ascending or descending inclines, and it should permit the foot to assume a position parallel to the floor when seated or after heel contact during other functions.

Several types of toe pick-up mechanisms were constructed and tested. The mechanisms consisted in general of simple four-bar linkages, referred to as pantographs, and the connecting link between the foot and knee joint was referred to as the fibula. After several types of these connecting links between the foot and knee joint were tried, a hydraulic type was selected ultimately as giving the most suitable operation.

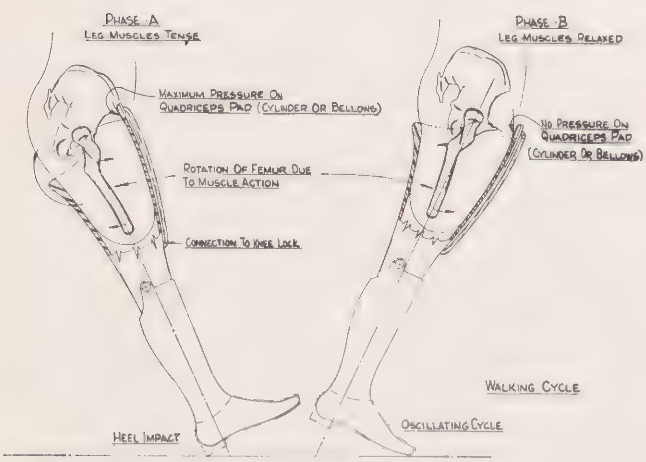


Fig. 104. Sketches illustrating muscle action at heel impact and toe push-off to actuate knee lock control.

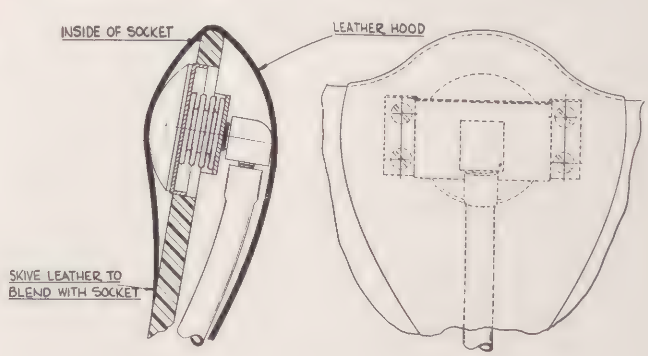


Fig. 106. Hydraulic sylphon bellows type ischial-quadriceps control for mechanical and hydraulic knee locks.

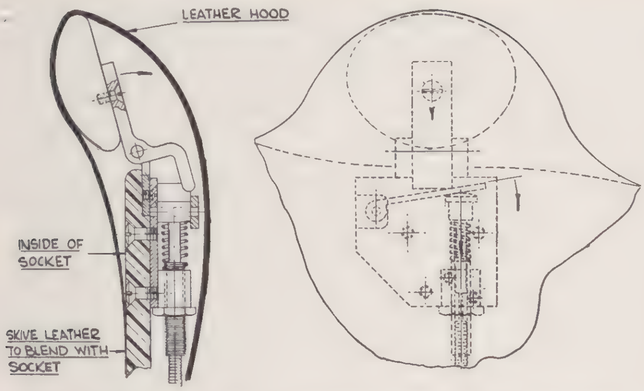


Fig. 107. Lever type ischial-quadriceps for mechanical and hydraulic knee locks.

One of the strut assemblies designed to act as a supporting member for the hydraulic prosthesis is shown in Fig. 108, and embodied an upper-knee casting and a lower connector of forged construction. The lower knee casting included a conventional stop for full extension and maximum knee flexion. The struts were made of tubular construction.

Since observations had led to the realization that some of the friction between the thigh and the socket could be eliminated by permitting rotation about the vertical axis of the artificial leg, two types of ankle rotation devices were developed. One consisted of rubber cushions which provided ten degrees of inward rotation of the foot and fifteen degrees of outward rotation. Another design adopted the use of two cantilever steel springs and provided ten degree inward and twenty-five degree outward rotation. Walking tests suggested that the addition of such a rotational device to the prosthesis improved the walking gait and resulted in a considerably greater degree of comfort for the amputee.

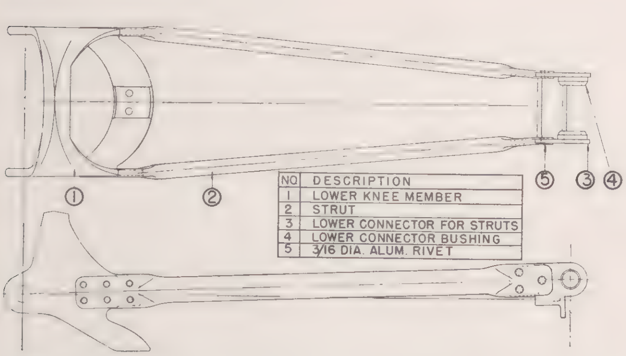


Fig. 108. Strut assembly for an artificial leg using a hydraulic knee-locking mechanism.

(6) Foot Design. Examinations of the various functional tests made on the several artificial feet developed in this project revealed that a foot had been designed which provided adequate shock absorption by means of flexion at the metatarsal joint. Final simplification of this functional foot, Fig. 109, reduced it to three principal elements: the ankle piece, the heel cushion, and the plantar rubber sandwich. Shock absorption, in this case, occurred during the entire period of the load cycle because the rubber sandwich extended along the full plantar surface.

UNIVERSITY OF CALIFORNIA

at Los Angeles, California

BACKGROUND. After the research program of the Committee on Artificial Limbs was in progress, the added interest in the cineplastic method of operating mechanical hands suggested that unavailable information covering the vast field of motion studies of the arm and hand was needed. Through the interests and cooperation of Dean L. M. K. Boelter, Professor Craig Taylor, and Professor A. D. Keller, all of the College of Engineering, a program was outlined. Work was begun in June, 1946. Commander August Dvorak, on loan from the United States Navy, gave valuable assistance in this venture.

General objectives of the program were twofold: (a) to determine the movements of the arm and hand necessary to accomplish everyday tasks and to reduce these movements to their simplest form in order to define the irreduceable requirements for prostheses; and (b) to establish a scale of complexity

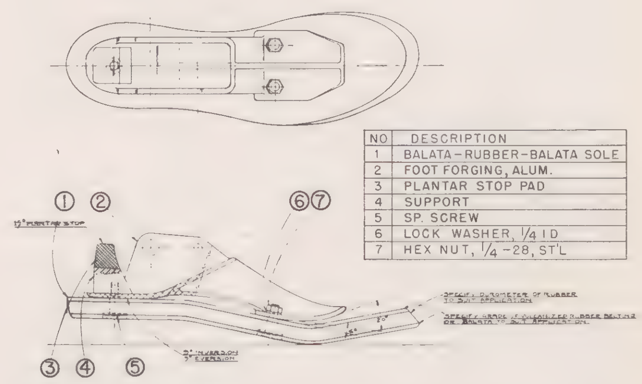


Fig. 109. Assembly drawing of a functional foot showing the ankle piece, the heel cushion and the plantar rubber sandwich.

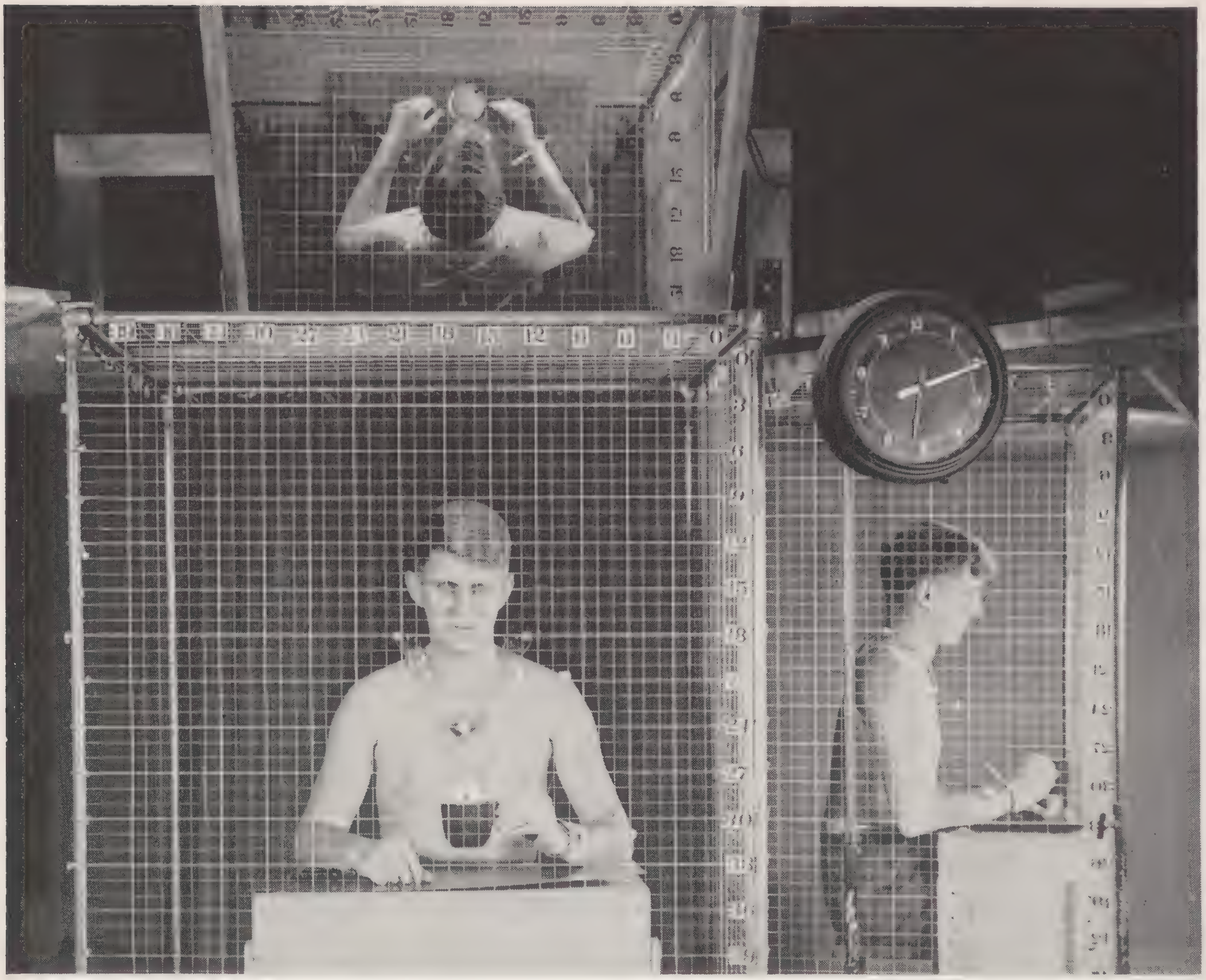


Fig. 110. Subject in the three dimensional grid system.

of motions providing for an increasing variety of life and occupational activities. This scale should be used as a basis for decision on the degree of complexity which is feasible or practicable to include in the artificial arm and hand.

More specific objectives of the program were: (c) to determine the relative merits of the hook and hand in terms of activities permitted, relative efficiency and performance, and complexity of mechanism entailed; (d) to seek evidence which would effect decisions on the problem of actively controlled joints versus locked joints, especially in connection with wrist supination, pronation, and flexion, and upper arm rotation; (e) to study prosthetic requirements for the cases of shoulder disarticulation; and (f) to study the limitations involved in two-action systems, such as the elbow-flexion hook opening mechanism on the present hook type arms.

Findings from this program should aid in the formation of a plan for standardization of design of artificial arms and hands operated by harnesses, by muscle tunnels, or by auxiliary power sources controlled by various trigger mechanisms.

PROJECTS. ***(1) Studies of Arm and Hand Activities.*** Because experience in the performance and analysis of a large number of activities led to the conclusions that many variable methods of performing an activity were superficial displays of peculiar habit patterns and that these may change with the

individual from day to day, it seemed wise to adopt an approach minimizing individual variations but focusing attention upon typical patterns of performance. To accomplish this objective a master list of standard activities, based upon the principle of standardized performance, was compiled. The next step was to standardize motion patterns in the performance of each test activity, that is, the determination of the "one best way" to accomplish a particular activity. As a further step in perfecting the method of the motion study one person was selected to serve in all kinematic views of the activities. He was of average anthropometric build and was habituated to the experimental procedure. He was carefully measured and fitted with the necessary body landmarks for kinematic analysis, determined by X-ray photographs of the bone and joint structure, and then was practiced in the standard pattern of the activity until thoroughly proficient in its performance. Moving pictures then were taken using a three dimensional grid system, and a thirty-five foot lens-to-object distance was selected to reduce perspective effects to a minimum. A view of the subject Fig. 110, is shown within the grid space.

After the actions were completed, the records obtained on a positive print film were viewed and the x, y, and z coordinates of the landmarks on the subject were recorded on data sheets for analysis by the kinematic analyzer. This analyzer, shown in Fig. 111, consists of a mechanical system of members and joints to duplicate the mechanics of the shoulder, arm, and forearm. By a suitable positioning scheme, each of the landmarks was placed in the same relative position which it occupied in the original space coordinate system. Built-in scales in the joints indicated the degree of joint rotation and these values were recorded giving a geometric description of the body mechanism.

(2) Comparative Tests of Amputees Using Representative Prostheses. The purposes of this study were (a) to standardize the method of evaluation of various types of prostheses, (b) to assess the functional loss associated with the amount of anatomical loss, and (c) to obtain further understanding of the practical difficulties faced by amputees in performing the activities of everyday life. It included a study of unilateral and bilateral above-elbow and below-elbow cases which were fitted with various types of artificial arms and hands. Comparative tests included measurements of force, determination of standard activity performance, and evaluation of standard manipulations. A simplified rating system was sufficient for the comparative analysis.

(3) Design Evaluation of Experimental Prosthesis Components. Functional tests of prosthetic devices fabricated by the several subcontractors have been made to yield a basis for (a) discarding unsuccessful developments, and (b) choosing promising mechanisms and principles which justify further development. The essential criterion is the ultimate facility which the device gives the amputee in normal activities. These judgments are based upon use of the prosthesis in the activities of everyday life. Additional analysis includes standard object manipulation and force measurements.

(4) Patterns of Hand Prehension. This project was undertaken to discover the typical basic hand prehensile, or grasping, patterns involved in two types of hand functions, (a) the "pick up," and (b) the "hold for use." Many photographic views of

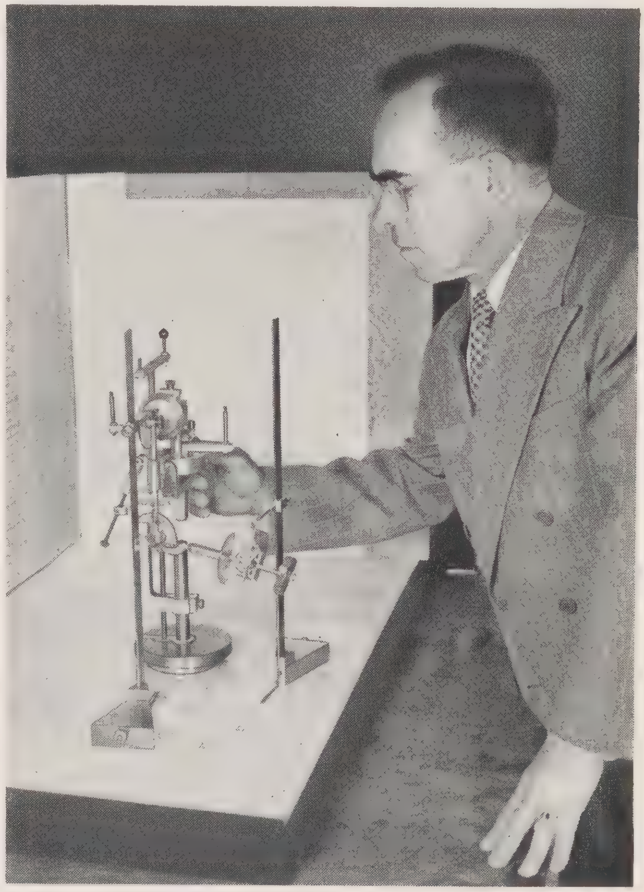


Fig. 111. Professor Keller inspects the UCLA kinematic analyzer.

subjects were taken and coded according to the simplified system mentioned below; frequency distributions were made of the various coded positions, and most frequently occurring positions were selected as the most typical elements of the prehensile patterns. Three basic patterns of hand prehension were considered, the lateral, the palmar, and the tip. Frequency of occurrences of these prehensile patterns indicated that palmar prehension is the most important for holding objects for use, while lateral prehension seemed to be most important for picking up objects. Trials of palmar prehension on a master list of activities showed it to be the most universally effective type.

(5) A Practical System for Coding Finger Positions. To permit a survey of all the important manipulations of the hand in everyday life, the kinematic analysis of hand activities had to be simplified. To accomplish this, a code of finger and thumb positions was devised designating the various degrees of finger flexion and spread, and of thumb flexion and position. The opposing surfaces of the thumb and fingers as well as surfaces in contact with the object also were coded. While each element of this system involved some rough approximations, it was found that when the hand pattern was reconstructed from the code of the original hand in conjunction with the object manipulated, a satisfactory specification of the hand pattern was obtained.

(6) Forces Involved in the Manipulation of Common Objects. To obtain more complete design criteria for the artificial hand, it seemed expedient to measure the forces involved in the handling of ordinary objects during a normal day. Strain gauges were used for all force measurements involving prehensions, while other loads, torques, and force requirements of a specific task were measured directly, certain dimensional and descriptive data being given to specify the task.

Most prehensile force requirements were found to be small: forces of pinch in pulling on socks or trousers were of the order of eight to twelve pounds; force on the thumb in opening a stiff faucet was ten pounds; force under the thumb in holding a two and one-half pound book was seven pounds; lifting double hung windows required nine pounds of force; and a lightly packed suitcase constituted a load of approximately twenty-two pounds. The largest forces encountered in handling eating tools and tableware ranged up to seven pounds.

MELLON INSTITUTE

Pittsburgh, Pennsylvania

BACKGROUND. In the early summer of 1946, the Mellon Institute of Industrial Research, in Pittsburgh, was approached with the problem of developing suitable protective gloves for mechanical hands. A subcontract was accepted by this institution, a program was formulated, and research was begun. Mr. W. Moody Wilson was appointed as a Fellow of the Institute for this project and Mr. G. W. Seagren, head of the Institute's Multiple Fellowship on Protective Coatings, was named Advisory Fellow. Mrs. D. K. Jacobs aided in the work as did Miss Anne Zak. Dr. G. H. Young, Executive Assistant to the Director, served as administrative adviser. The close cooperation extended by Mr. Claire Milton of the Army Prosthetics Research Laboratory at Walter Reed General Hospital in Washington, D. C. was helpful throughout the program.

Work on the project was brought to a successful conclusion in June, 1947.

PROJECTS. (1) ***Hand Study.*** In the beginning it seemed desirable to familiarize the participants in this research with the advantages and disadvantages of each type of artificial hand now commercially available in order to develop perspective for adapting the cosmetic glove to mechanical hands. Seven commercial artificial hands varying widely in weight and adaptability were selected as representative of the best of the hands then available. Each hand was studied and sketched in its component parts and technical descriptions of each were drawn up for the use of other subcontractors working under Committee auspices with the hope of obviating subsequent functional design errors.

(2) ***Properties Evaluation of Plastics.*** This phase of the program involved a searching investigation of plastic materials which can be cast or cast-molded to form cosmetic plastic skin gloves. Such rubber-like materials, called elastomers, were investigated in three different groups as outlined below.

The mechanical properties on which measurements and observations were recorded for these three groups of plastics included: tensile strength; percentage elongation; modulus of elasticity, influence of high and low temperatures; tear resistance; thermal conductivity; aging properties; cleanability; hardness; dimensional stability. Evaluation of chemical properties included: water absorption; chemical inertness;

plasticizer migration. These plastics were studied also from the standpoint of their ability to be cast, molded, formed, and to maintain satisfactory detail of design in each process. Aesthetic properties included in the evaluation of elastomers were: permanent or temporary color possibilities; texture; translucency; tactile properties; odor. All plastics considered were, of course, necessarily toxicologically acceptable.

(a) Plastisols. A plastisol may be defined as a dispersion of a potentially soluble resin, in finely divided form, in a pasticizer-type high-boiling latent solvent. Under the influence of heat the particles are dissolved and fuse together into an elastic rubbery solid. Many combinations of materials to form an adequate series of plastisols were compounded and investigated. Plastisols in general have desirable properties except for rather low tear resistance, and a tendency for migration of some plasticizers with resulting loss of physical properties because of plasticizer disappearance. It was found that certain fillers could be used for reinforcing plastisols, and during the program materials were compounded with improved tear resistance.

Chemical modifications of plastisols by compounding with selected low pressure thermosetting resins also were investigated. Although a few polyester resins proved possible additives, these studies indicated need for further developments in the resin field before really significant improvement could be expected.

Several of the plastisol formulations developed in the course of this investigation were shown to have most of the physical characteristics believed required in a covering for an artificial hand. From heating these formulations under various combinations of temperatures up to 350 degrees Fahrenheit and pressures to 222 pounds per square inch, it was demonstrated that the highest strength properties were obtained from the pressure-molded samples. This might be expected, since pressure-molding results in a more compact and homogeneous material. It was further established that the cast specimens baked at the highest oven temperatures had physical properties generally superior to those baked at the lower temperatures.

(b) Latexes. Most of the available commercial rubber latexes were included in this investigation of plastic materials. Natural rubber latex appeared to be the most promising one of this group except for its lack of satisfactory resistance to oxidation and to deterioration by light. To overcome these deleterious properties of natural rubber latex, protective coatings for rubber also were studied.

In general, the latexes failed to meet several important property specifications and for this reason were not evaluated in respect to all physical properties.

(c) Thermosetting Resins. These compositions are based on stable, solvent-free, fluid resins which, cured in an inert atmosphere under the influence of heat and a peroxide catalyst, can produce clear, colorless, insoluble films which are reasonably flexible and tough. Various liquid resins were mixed and cured in an attempt to produce the best combination of properties.

It was recognized that the available vinyl type plastics were generally inferior to vulcanized rubbers in strength, extensibility, and resistance to cutting and tearing. However, the great advantage of plastics of this class with respect to appearance, together with their excellent abrasion and chemical resistance, and far superior aging properties, led to the conclusion that the plastisols were the best of the materials available for the fabrication of cosmetic gloves.

(3) Cosmetic Coverings. The object of this phase of the project was to evaluate the available pigments in all of the plastics considered important. These colors were grouped in two categories: basic shades and variations of tints of each basic shade for application to parts of the hand such as knuckles, nails, the palm, and the back of the hand. It was necessary to determine by various procedures which of the plastics took and retained color most readily. A considerable volume of data on the coloration of plastics thus was accumulated.

ADEL PRECISION PRODUCTS CORPORATION

Burbank, California

BACKGROUND. A successful and envious record of achievement in the design and manufacture of high pressure precision hydraulic mechanisms, particularly in the field of aircraft control units, led the Committee to request the Adel Precision Products Corporation to undertake the development of a hydraulically operated artificial leg for above-knee amputees. This project was started in July, 1946, under the leadership of Mr. W. C. Oliver as chief engineer. A minimum requirement established for the leg design was that a hydraulically locking cylinder must

allow the leg to support weight in a flexed position. The design of the locking cylinder and its operating valves, the method of control of the operating valves, and the points of attachment of the locking cylinder ends were to be determined during the course of the development.

This contract was terminated in June, 1947, with the completion of the successful testing of the first working model of the leg.

PROJECT. After screening the available literature on the subject of lower extremity prostheses and after analyzing the data recorded by the University of California at Berkeley on the mechanics of walking, consideration was given to the placement and points of attachment of the hydraulic cylinder in the leg.

A replotting and evaluation of data obtained from the University of California relating to the correlation between the femur-tibia (knee) angle versus the tibia-tarsus (ankle) angle, revealed that placement of the hydraulically locking cylinder from the thigh to the shank, an approach previously tried by other investigators, would not give motions closely approaching the normal leg. Further deliberations led to the attachment of one end of the hydraulic cylinder to the thigh piece at the rear of the knee bolt and the other end to the foot at the front of the ankle bolt. This allows knee flexion to occur in a fixed ratio automatically with foot plantar flexion when the hydraulic cylinder is locked, the latter being accomplished by contact of the heel with the ground. The four-bar linkage causing this interrelated knee and ankle motion reverses itself after the ball of the foot reaches the ground and the body moves forward, causing the knee to extend as the foot dorsiflexes, a new basic concept in artificial leg design.

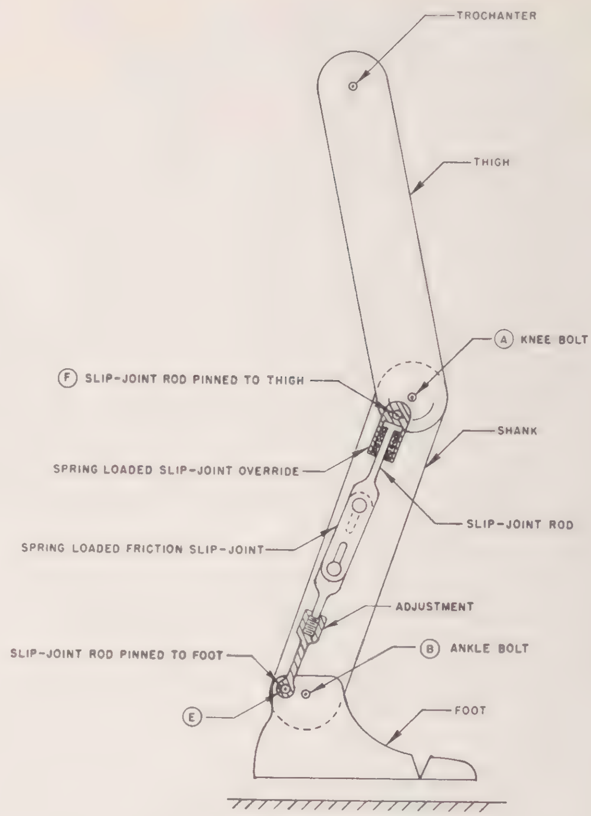


Fig. 113. Schematic diagram of slip-joint rod.

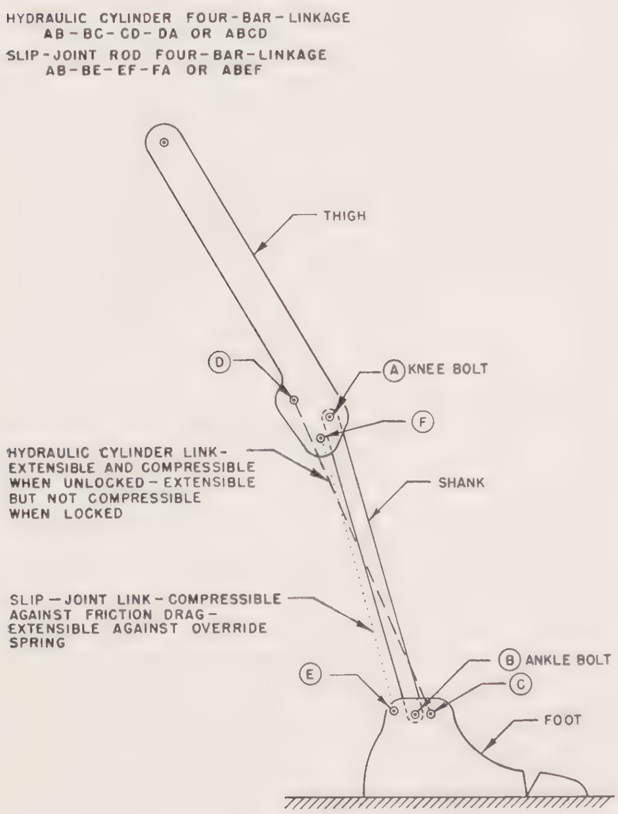


Fig. 112. Schematic diagram of four-bar linkages causing leg motions.

In Fig. 112, a schematic diagram shows two separate and distinct four-bar linkages used in this design, each independently causing interrelated knee and ankle rotations during certain phases of the walking cycle. These two systems have the leg shank as a common, stable, and unyielding link; the yieldable links are shown in the diagram as CD, the hydraulic cylinder link, and EF, the slip-joint link. The hydraulic cylinder link, CD, when operating, causes

knee flexion and foot dorsiflexion to occur simultaneously in a varying ratio depending on the degree of each. Link EF, when operating, causes foot dorsiflexion and knee flexion to occur simultaneously until link EF crosses AB when foot plantar flexion and knee flexion will occur simultaneously. The hydraulic cylinder link, CD, if unlocked, is free to lengthen or shorten, having only a resistance caused by the friction of the shaft and piston seals.

The slip-joint rod, shown schematically in Fig. 113, is free to lengthen against spring tension and to shorten against a frictional drag. The spring tension is greater than the frictional drag which in turn is greater than the friction caused by the piston and shaft seals of the hydraulic cylinder link. This suggests that during the period in the walking cycle when the foot is not touching the ground, at which time the hydraulic cylinder is unlocked, the slip-joint rod four-bar linkage, ABEF, in Fig. 112, is active, with the hydraulic link, CD, yielding. When force is applied at any point on the bottom of the foot, the hydraulic link, CD, is locked and the hydraulic cylinder four-bar linkage, ABCD, becomes active.

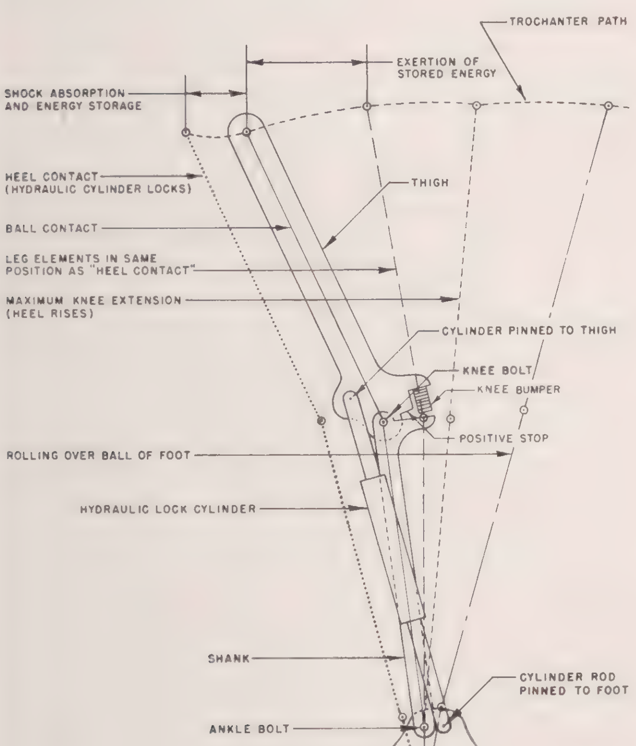


Fig. 114. Motion pattern with four-bar linkage at heel contact with the hydraulic cylinder locked.

The motions of the leg in level walking may be followed by referring to Fig. 114. At the time the heel hits the ground, the construction of the slip-joint rod, illustrated in Fig. 113, directs that the foot be at a definite, but adjustably variable, angle to the shank. As force is applied to the heel, the hydraulic cylinder locks and the motion patterns of the leg are determined by the hydraulic cylinder four-bar linkage, ABCD, shown in Fig. 112. The foot then plantar flexes and the knee flexes until the foot is flat on the ground. This motion corresponds very closely to the pattern of the normal leg. As the body moves forward, the four-bar linkage reverses bringing the leg elements to the same relative position as at heel contact. As the body proceeds further, the yieldable knee bumper, shown in Fig. 114, is further compressed; the heel rises when the maximum knee extension position in the reversed linkage motion is reached and the acting four-bar linkage is locked because the relative rotation of two of its links has been stopped. No further relative leg motions occur until the knee is flexed at the start of the "swing through" phase. Knee flexion occurs when the load on the ball of the foot has been reduced to an adjustably variable quantity, thus unlocking the hydraulic cylinder link. Relative motions during the swing through phase then are determined by the slip-joint rod four-bar linkage, ABEF, which comes into active play. Several knee angles with corresponding ankle angles are shown in Fig. 115.

In the normal walking, muscular effort is used to raise, and to check the lowering of, the body weight. One form of energy dissipation in a normal leg occurs during the shortening of heel-to-hip length by a slight knee flexure and plantar flexion of the foot as the heel contacts the ground. Energy exertion in a normal leg occurs immediately after this dissipation as the knee extends and the foot dorsiflexes during the "roll over" period and also at the plantar flexion kick off. It seemed desirable to attempt to store the normally dissipated energy in some mechanism in the artificial leg which could exert it when needed to reduce the muscular effort required of the sound leg. Reflection on this problem suggested that the normally dissipated energy of shock absorption should be stored in the artificial leg during the motion of knee flexure and plantar flexion of the foot between the instant the heel first contacts the ground

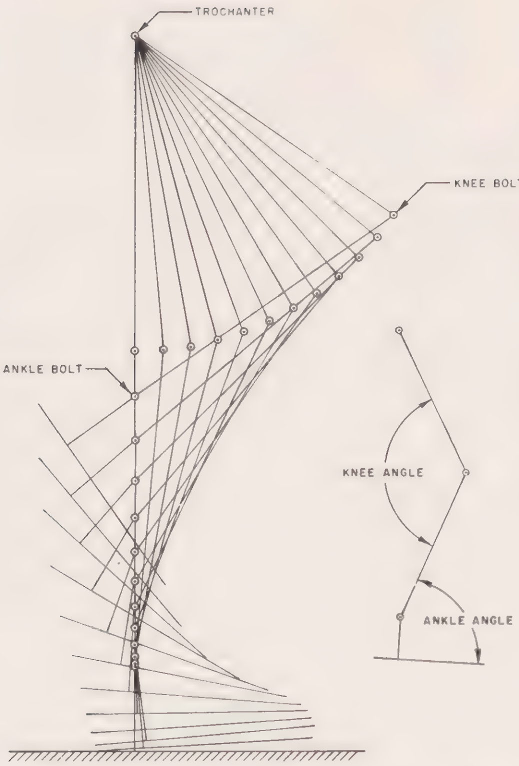


Fig. 115. Leg motions showing the knee angles with corresponding ankle angles.

adjustably greater than that necessary on the heel to perform the same function. In addition to the automatic control, a voluntary cable control is supplied to override the automatic control so that the knee can be flexed even though force is being applied through the foot.

A standard wooden foot was modified for use on the Adel leg by reworking to allow for inclosure of the energy storage and automatic control leverage mechanisms. An aluminum piece was fastened to the top of the wooden foot to which the ankle bolt, hydraulic cylinder, and slip-joint rod were attached. The toe section, as shown in Fig. 118, allows upward movement to 45 degrees from the horizontal, and movement is resisted by a compression spring. The shank consists of two aluminum side members fastened to the foot and knee piece by the ankle and knee bolts respectively. Moderate torsion in the shank allows axial rotation of the knee with respect to the foot and relieves somewhat the torsional loads on

and the time the ball of the foot touches the ground. In the action of this leg, the equal and opposite forces acting externally to the leg along the force line cause a torque to be exerted tending to plantar flex the foot. This is indicated in Fig. 116. A precompressed spring, having the proper load and rate characteristics, inserted in the foot opposes the plantar flexion and allows for shock absorption and for the storing of energy. As the body moves forward, the rising motions as determined by the linkages are assisted by the spring returning the stored energy.

While the first model leg used a steel spring for energy storage, an air-hydraulic spring shown in Fig. 117, offers the advantages of: (a) enabling a change of spring rate by varying the ratio of the quantity of oil to that of air, and (b) allowing a change in the initial load by varying the initial air pressure. Placement of such a unit probably should be longitudinal in the foot, activated by an extension of the leg shank below the ankle bolt.

The automatic valve control mechanism in the foot to actuate the hydraulically locking cylinder is shown in Fig. 118. Application of force on the ball or toe of the foot necessary to lock the cylinder is

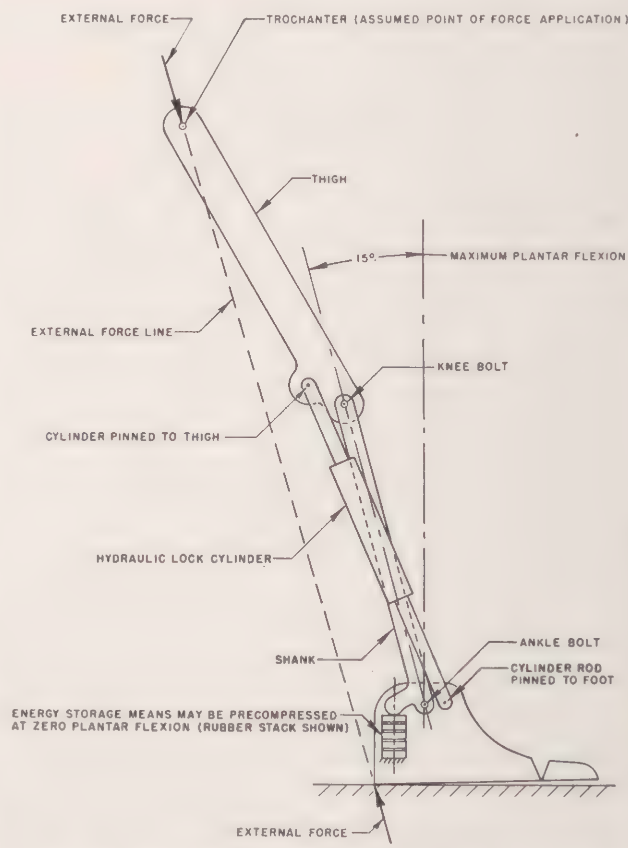


Fig. 116. Schematic diagram showing method of energy storage during plantar flexion of the foot.

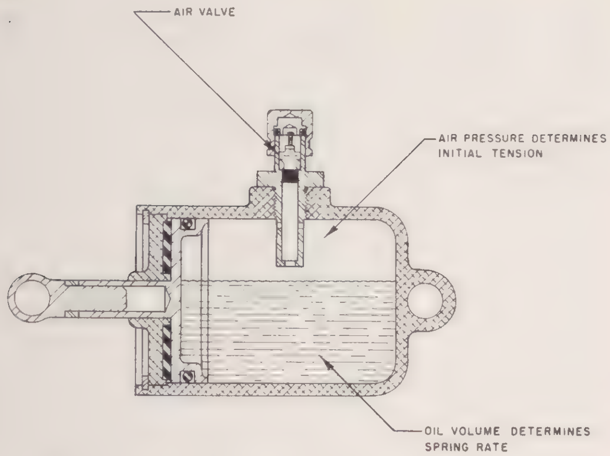


Fig. 117. Air-hydraulic spring for energy storage.

the stump. The knee piece was machined from a solid aluminum block to accommodate the knee bolt, hydraulic cylinder, and slip-joint rod attachments as well as fastening to the thigh piece. The thigh piece and socket were of standard construction, the socket being made of wood and riveted to an aluminum thigh piece.

Tests on the first working model of this leg at the University of California indicate that further experimental work is necessary in order to take full advantage of the energy storage, shock absorption and stance phase knee motions in level walking. The natural reaction of an amputee is to apply a torque from the stump tending to straighten the leg; this results in a smaller compression of the energy storage spring and a lessened resulting knee flexion than were previously calculated from axial load. Unlocking of the hydraulic cylinder at the beginning of the swing through phase apparently occurs at a time when the stump is applying a torque to the leg for the start of the swing through phase, and this combination results in a more rapid acceleration of the leg than normal. The swing through phase is normal in appearance. The maximum knee flexion and ground clearance due to toe lift in the artificial leg is approximately the same as in the normal leg.

In walking up a ramp this leg action simulates the normal. The steps are essentially equal and the knee straightens as the body moves forward in the stance phase. Placement of the artificial foot for a step occurs at a flexed knee condition which is slightly less than that of the normal knee since some initial body rise for the step on the artificial leg must come from the muscles of the normal leg. Down ramp walking shows almost identical motions between the two legs. Good shock absorption resulting from clearly visible initial plantar flexion, knee flexion, and energy storage spring compression is evident.

In ascending stairs, the expected difficulty of placing the artificial foot above the normal foot for its next step was verified. It was found necessary to flex the knee by pushing the toe against the rise of the step on which the artificial foot is to be placed. The knee extends in the stance phase, although not to the extent of a normal leg because of the lack of muscle power. Ascending stairs step-over-step is not practical with this leg in its present state of development. Descending stairs step-over-step seems normal, the foot remaining flat on the step in the stance phase. When the cylinder unlocks on the removal of weight, the tensed spring of the slip-joint rod causes the foot to return toward normal, kicking the heel clear of the step in a normal manner.

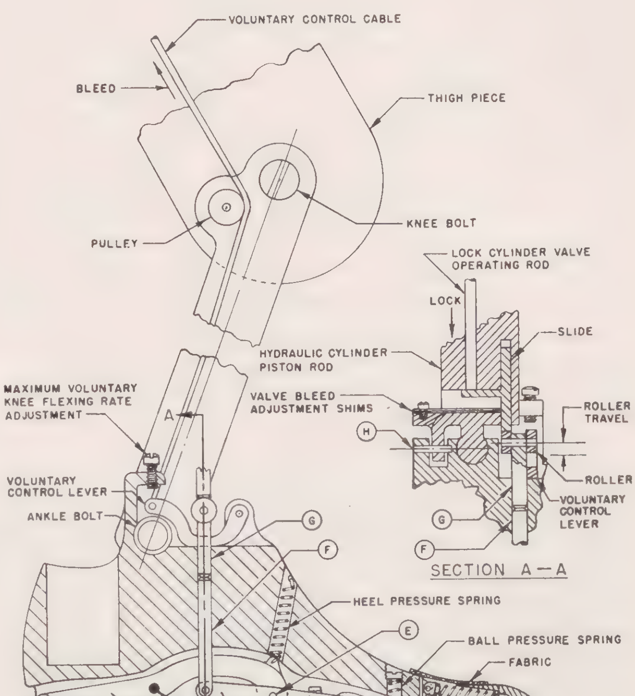


Fig. 118. Automatic lock cylinder valve control mechanism.

SIERRA ENGINEERING COMPANY

Sierra Madre, California

BACKGROUND. With the return of the Surgeon General's Commission from Europe it became apparent that renewed effort should be devoted to the design of arm and hand protheses for use with the cineplastic method of utilizing muscle tunnels for motivation of the upper extremities. With this objective in mind a second tier subcontract under the Northrop Aircraft subcontract was negotiated with the Sierra Engineering Company in July, 1946, the specific purpose of which was to develop an improved artificial hand combining functional usefulness with lifelike appearance. This research was to be directed toward cineplastic applications, but the hand itself was intended to be suitable for use with simple modifications by all amputees.

This work progressed under the guidance of Mr. John E. Conzelman, Jr. as vice-president of the Sierra Engineering Company with Mr. Herbert B. Ellis as project engineer. This contract was terminated in June, 1947.

PROJECTS. ***(1) Hand Design #1.*** After a synoptic study of the literature available on prosthetic art and the anatomy of the hand and arm, the first hand was designed and built following the basic structure of the human hand and providing the utmost in flexibility and freedom of motion. It was hoped that from this design the necessary compromises could be made to produce a suitable operation from one or two control cords as against the nineteen effective major controls in the natural hand. This hand was not intended to be worn by an amputee but was so constructed that various mechanical arrangements could be tried and from experiments, bases could be formed for subsequent designs. These experiments indicated that (a) all movements in artificial hands should be positively controlled, (b) all moving joints should be as free from friction as possible, (c) the friction moment arm of moving joints should be a minimum, and (d) mechanical parts requiring take-up adjustments were undesirable.

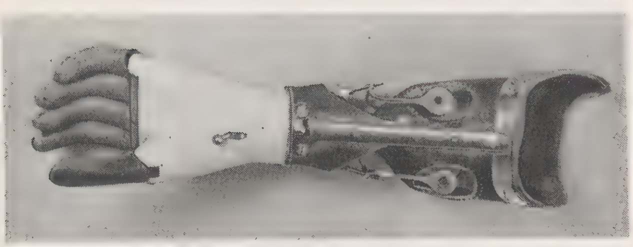


Fig. 119. Sierra hand design number 2 with modified Hüfner hand.

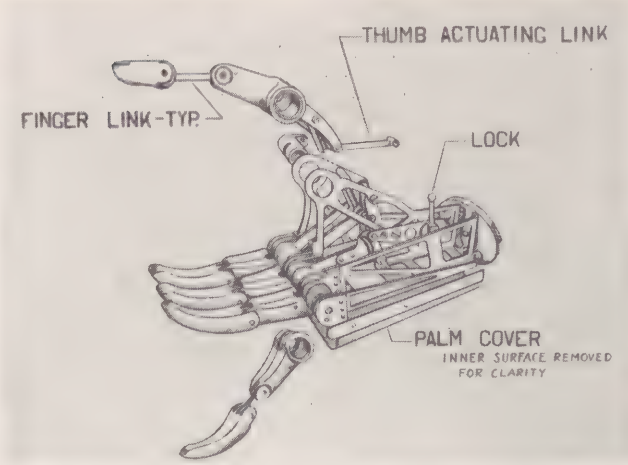


Fig. 120. Exploded view of hand design number 3A.

(2) Hand Design #2. By use of an exerciser mechanism it was found that a cineplastic amputee could train himself to use each of his two muscle tunnels independently of each other. To test this performance of muscle tunnels in unrelated operations, an available Hüfner hand was modified so that one muscle tunnel operated the thumb and the other muscle tunnel operated the finger group. Upon fitting this design, shown in Fig. 119, it was found to be necessary, in a hand and arm prosthesis using two muscle tunnels independently, to acquire some means of holding the prosthesis in place other than the muscle tunnels. It was found also that the different magnitudes of forces available in the individual muscle tunnels must be considered in design.

(3) Hand Design #3A. It became necessary to supply artificial hands for the few men who had volunteered to undergo the cineplastic operation. To satisfy this demand quickly a modified Hüfner hand was built. An exploded view of this hand is shown in Fig. 120. It was constructed of an aluminum alloy sheet metal frame with a laminated plastic skin shell and was designed with articulated fingers and thumb to pick and hold objects such as water tumblers, not possible with the original Hüfner hand.

To reduce the weight of these hands, steel pins

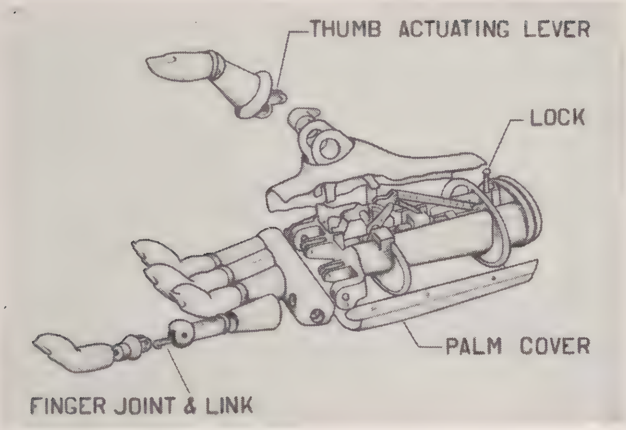


Fig. 121. Exploded view of hand design number 3B.

were made hollow and all steel parts were made as small as stresses would allow; bronze bushings were checked for minimum wall thicknesses and magnesium was substituted for aluminum where practicable. The lightest of the six experimental models built weighed 269 grams (about nine ounces).

(4) Hand Design #3B. To simplify some of the problems of linkage between the arm and the hand, especially where wrist rotation was provided, a hand was designed and built to be operated by a rod located at the center of the wrist in lieu of a cable on the side of the hand. In this redesigned model care was taken to reproduce more accurately the contours of the natural hand. A manual lock was provided that produced a tightening of the grip as the hand was locked. The hand #3B is illustrated in Fig. 121.

(5) Hand Design #4. After consulting members of the staff of the University of California Prosthetic Laboratory at Los Angeles, a redesign was made utilizing new studies of normal and necessary hand motions. This new design utilized the palmar finger grip in conjunction with a fixed thumb. This palmar grip consists of holding objects between the thumb and palmar surfaces of the index and middle fingers. This hand, shown in Fig. 122 without its covering, uses surface contact as a holding means rather than point or line contact as was used in previously designed hands.

The palmar grip required minimum linkage in the hand since only the index and middle fingers were articulated at the medial joints and all four proximal joints could be pivoted from a common knuckle bar. This mechanism, coupled to a rigidly preplaced thumb, created an extremely simple system in which all of the mechanism was placed within the wrist joint, the knuckle bar being operated through a single compression tube. Such a design placed the center of gravity further up the arm which was a definite advantage to the amputee.

(6) Force Multiplier. The term "force multiplier" refers to a mechanism which produces no change in the reaction force or in the length of the pulling cable until a predetermined pull is reached; then it acts as a simple lever to increase the force and to reduce the motion without a loss of motion when the shift is made. Because it was noted that the force provided by cineplastic muscle motors falls off rapidly with increased excursion or lengthening, and because the various muscle motors do not have the same degree of available force, it was decided early in this research program that the use of such a force multiplying mechanism was indicated in cineplastic prostheses. After a study was made of various mechanisms and methods of producing force multiplication, the latch and brake type was selected. It consists essentially of two pulleys over which a link chain passes. These pulleys are mounted on a lever that pivots at a fixed place in the arm; in the nonmultiplying position, the lever is locked in a fixed position by a latch and the pulleys are free running; in the multiplying position, the latch is released, actuating a brake which fixes one of the pulleys solidly to the lever thus preventing the cable from running through the mechanism. This converts the mechanism into a simple lever which produces a force multiplication with a corresponding

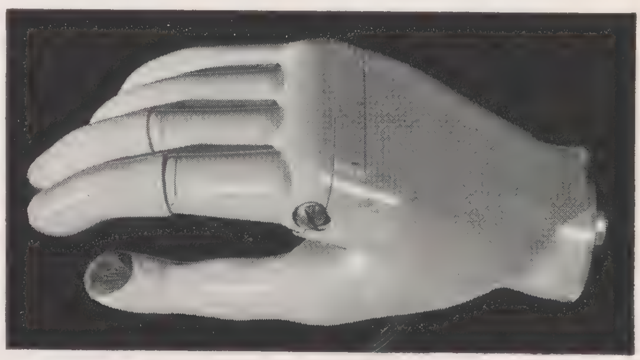


Fig. 122. Sierra hand design number 4.

reduction in the travel of the increased reaction. A schematic diagram, Fig. 123, illustrates this force multiplier employing a 3-to-1 ratio.

(7) Link Chain. It was found that cable, which at first was used in the force multiplier, was unsatisfactory, and this was supplanted by a link chain. The links of this chain were stamped from SAE 4130 sheet stock and assembled on shouldered pins with the outside links riveted in place against the shoulder so that while close fits between link groups were obtained, freedom of rotation of the inside links was assured. This chain has a 5/32 in. pitch (6.4 links per inch). One style has an ultimate strength of approximately 350 pounds in tension.

(8) Sense of Touch Mechanism. It is generally agreed by men in the medical profession that the sensory functions of a hand are at least as important as the mechanical functions. An analysis of this problem indicated that it might be feasible by the use of an electric or a hydraulic system, to develop a sense of touch in the fingers by light pressure on other sensitive parts of the body.

A hydraulic system tried consisted essentially of two bladders or diaphragms connected by a rubber tube, one diaphragm in the finger and one against the skin of the natural arm. While obviously this system gave no sensation of hotness or coldness there was the possibility that some sense of pressure could be developed in the amputee, very important in grasping fragile objects.

Electrical methods were investigated but eventually dropped because (a) the resistance between the electrode and the skin was subject to wide variations due to temperature and humidity, making an accurate control of the sensation difficult, and (b) the impulse produced gave a sensation of pain rather than touch.

The field of subsonic vibrations (from sixty to one hundred cycles per second) also was considered. This system gave a more definite sensation of finger contact than the hydraulic system, and was regarded as having future promise although the present work could not be completed.

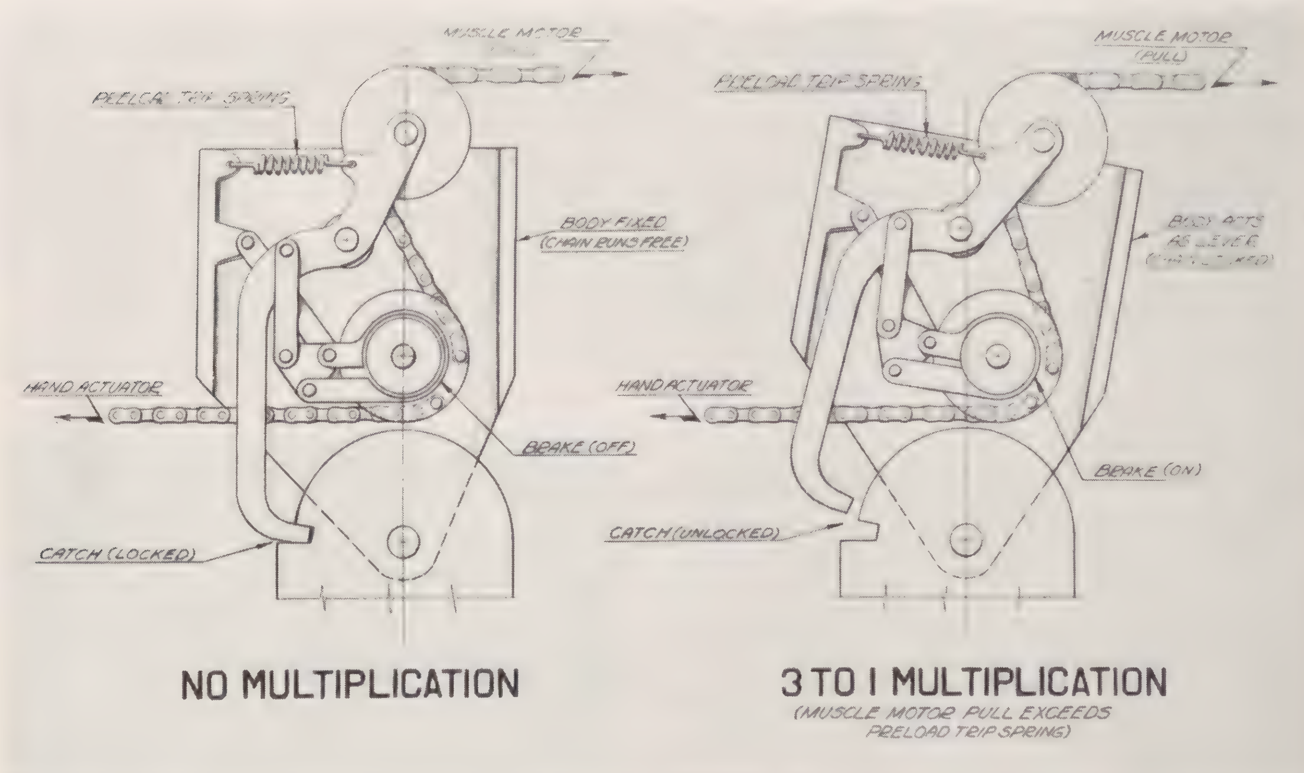


Fig. 123. Sierra force multiplier.

VARD, INCORPORATED

Pasadena, California

BACKGROUND. In the spring of 1946, it became obvious to Members of the Committee that a need existed for the development of an artificial arm and hand suitable for the amputee undergoing the cineplastic operation. Because of the wide experience and varied background in the fields of research and production engineering, Vard, Inc. was invited to participate in such a program. This program was divided into two parts: the hand was to be developed by the Sierra Engineering Company, and the arm from the wrist up was to be produced by Vard, Inc., the two subcontractors working very closely together. Work was started on this project in July, 1946, under a second tier subcontract negotiated under the Northrop Aircraft subcontract.

The contract was terminated prematurely by mutual agreement in February, 1947, and the project was transferred to the Sierra Engineering Company.

Mr. William H. Shallenberger was the technical director of the arm project at both Vard, Inc. and Sierra Engineering Company.

PROJECT. This subcontractor's approach to the problem of developing a cineplastic arm was carried through four distinct steps.

Because the field of artificial limbs was new to all of the personnel connected with the project, a period of education involving a study of the anatomy of the upper extremities as well as a survey of previous work on artificial limbs first was necessary. The second step was the classification of all arm amputees into a relatively small number of groups. This was an attempt to avoid having to design a completely new prosthesis for every amputee fitted and included a consideration of the muscles available for use through the cineplastic operation as well as the functions necessary to be provided by the prosthesis. The third step in reaching the primary objective was to make a general analysis of the problem by correlating the power sources required to operate the various parts of the hand and arm with the sources of power available from the cineplastic muscle motors and harnesses. Using this analysis, the fourth and culminating step was the design and construction of a specific prosthesis for a specific amputee. This last step involved a detailed study of the various power sources, structures, harnesses, and the application of engineering principles to each.

Fig. 124. Vard experimental cineplastic below-elbow arm attached to a Sierra hand.

Considerable time was spent in the study of control systems for cineplastic arms. Mechanical and hydraulic systems of transferring forces from the muscle tunnels to the hand and forearm were investigated. It was decided that control of the hand should be provided by the use of muscle motors while active elbow flexure should be controlled by the forearm stump or by shoulder harnesses. Many types of harnesses were studied and criteria set forth for their design. Numerous types of locks, some automatic or self-locking and some passive in function, were investigated. Study of various structures for the arm indicated that a plastic laminate shell with an accurately fitted plastic laminate stump socket was probably the most practical.

After this preliminary and extensive investigation, four arm prostheses were fitted to cineplastic amputees following the findings set forth. Two of these were built for German amputees brought to this country for observation and experimentation, and two were built for amputees of the U. S. Army. All were fitted with artificial hands produced by Sierra Engineering Company and all arms were purely experimental units. No attempt was made to develop production designs and models nor was an attempt made to achieve minimum weight.

The cineplastic amputee, in Fig. 124, is shown wearing an experimental below-elbow arm attached to a Sierra hand. This hand makes use of a control rod at the center of the disconnect joint. The rod is free to rotate as the arm is supinated passively by the amputee. Contraction of the extensor muscle motor opens the hand and contraction of the flexor muscle motor closes it. The wrist joint allows passive supination through a rotation of 360 degrees with locking positions every 18 degrees. A sliding pin lock is provided for this purpose. The arm, including

the disconnect joint but excluding the hand, weighs only thirteen ounces and it is believed that several ounces can be removed by the use of smaller, lighter bearings. Since the plastic members were thicker than desired, weight may be removed here also.

In Fig. 125, a close-up of the worm gear supination control for a below-elbow cineplastic arm utilizing the biceps muscle tunnel is shown. The cable at the right is connected to a harness to produce supination, while the cable at the left is attached to the pronation spring. Greater tension in one cable than in the other produces the desired rotation while equal tension in each causes locking. The hand disconnect joint is supported by the plastic shell.

One of the important results coming out of this research project was the recommendation that standardized wrist units and elbow joints should be developed. The wrist unit could be adapted by all cineplastic amputees, right or left handed, unilateral or bilateral, above or below-elbow stumps. The wrist unit should include a hand disconnect joint and passive wrist flexure, which has been shown to be desirable through the motion studies on hands at the University of California at Los Angeles. It should include also the supination bearing and control mechanism. Design criteria for this standardized wrist unit have been set forth in the final report of this subcontractor. The elbow joint and hinges should have adequate extension stops and good bearing area. Bearing surfaces of bronze on steel have indicated long life.

Through the findings of this project, further research also has been recommended on skeletal type forearms, hydraulic systems for arms, cosmetic coverings for the forearm, and a more thorough investigation of automatic locks.

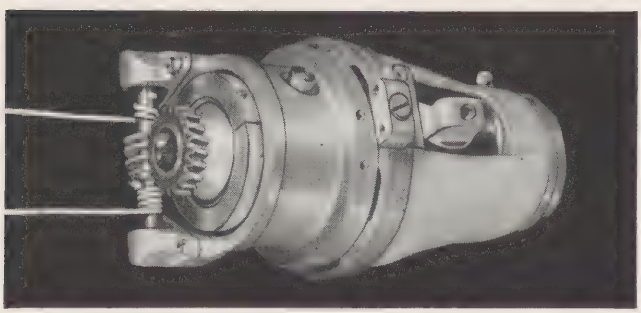


Fig. 125. Worm gear supination control for a Vard below-elbow cineplastic arm.

ARMOUR RESEARCH FOUNDATION

Chicago, Illinois

BACKGROUND. Some years ago, Dr. W. J. Mead, Professor of Geology at Massachusetts Institute of Technology adapted and patented the application of the dilatancy principle to the molding of impressions of the feet and other body members. This dilatancy principle makes use of the fact that a medium of small particles, such as sand or glass beads, can have its resistance to shear altered by a change in the external pressure. A quantity of the granulated substance enclosed in a thin air-tight rubber bag at atmospheric pressure behaves much like a plastic material and can be molded readily to any desired configuration. If the bag is partially evacuated, the resulting external atmospheric pressure causes the particles to be more closely packed and the medium then exhibits the rigidity of a solid body. The degree of plasticity can be adjusted by regulating the pressure.

The United Shoe Machinery Corporation of Beverly, Massachusetts, although not under contract to the National Academy of Sciences, undertook an investigation of the application of this principle of dilatancy to the molding of stump sockets. Through the personal endeavors of Mr. Mieth Maeser, a Member of the Committee on Artificial Limbs, the development program at the United Shoe Machinery Corporation was closely coordinated with the research program of the Committee. The preliminary tests performed by the United Shoe Machinery Corporation showed neither failure nor success of the method, but were encouraging enough to warrant a further and more complete investigation of the process by the Committee. It was hoped that the adaption of the dilatancy principle would simplify fitting procedures and accelerate the acceptance and ultimate use of the suction socket.

In August, 1946, the Armour Research Foundation was invited to undertake the continuation of this investigation in an attempt to improve the application of the dilatancy principle in obtaining rectified casts of below-knee stumps.

The program was successfully concluded in April, 1947, with the recommendation that further development of such a fitting machine utilizing the dilatancy principle should be halted until sufficient medical research data relating to bearing pressure and pain studies of the amputed stump become available.

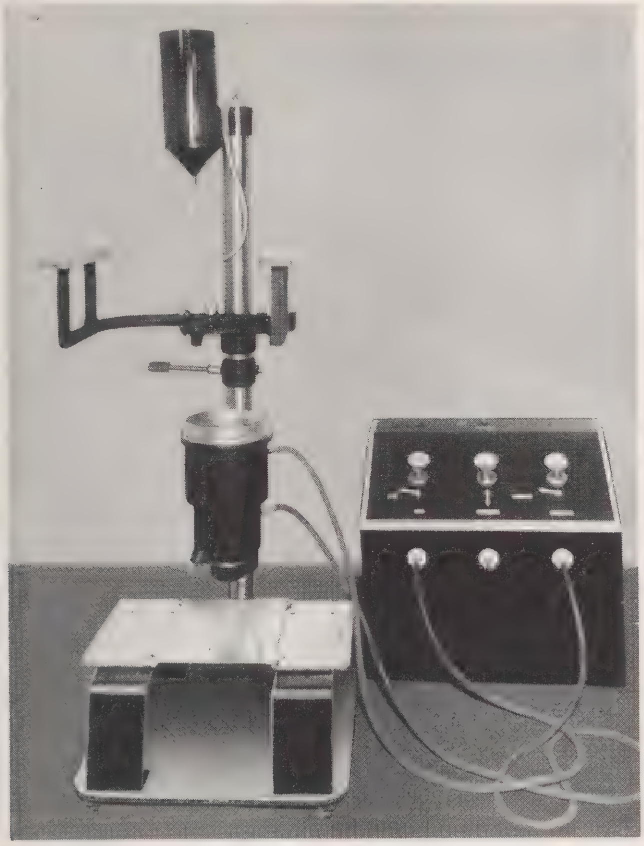


Fig. 126. Dilatancy machine.

PROJECT. After the available literature on limb fitting and its associated problems was studied, and after the experimental data previously obtained were analyzed, the dilatancy experimental fitting machine was erected in the laboratory and replicas of the stumps of actual below-knee amputees were prepared. The dilatancy machine, shown in Fig. 126, built by the United Shoe Machinery Corporation, consisted of a heavy steel base, to which was bolted a vertical, tubular column. Mounted on this column were, in order, the canister assembly, the mandrel holder, the supports for arms, and the bead container.

The canister assembly, schematically shown in Fig. 127, was the most important part of the dilatancy machine. A rubber diaphragm about its upper half formed a totally enclosed chamber which was connected by a rubber hose to an adjustable air pressure source. The lower half of the canister was connected by a rubber hose to a regulator valve and vacuum pump. The wooden plug indicated provided a height gauge and rest point for the end of the stump before the canister was filled with beads, and the bead drain allowed removal of the glass beads after a replica had been made.

In producing a replica of a below-knee stump, the stump first was prepared by attaching felt padding to the tibial areas to provide the necessary clearance. A thin latex bag or sock then was drawn over the stump and freed from wrinkles. The amputee then inserted his stump into the canister, resting the stump end against the wooden plug, and the small glass beads were poured around the stump until the canister was filled to the top of the lip. The open end of the latex bag was drawn down over the lip of the canister and air pressure was applied causing the bead mass to contract about the amputee's stump simulating predetermined conditions. The amputee then transferred his entire body weight to the stump, and the full available vacuum was applied, thus setting the bead mass into a rigid structure. Maintaining the full vacuum, the air pressure was reduced and the amputee withdrew his stump from the canister while the cavity which remained was rigid and maintained its molded shape. A previously greased mandrel was inserted into the cavity and plaster of Paris was poured until the cavity surrounding the mandrel was completely filled. The high vacuum

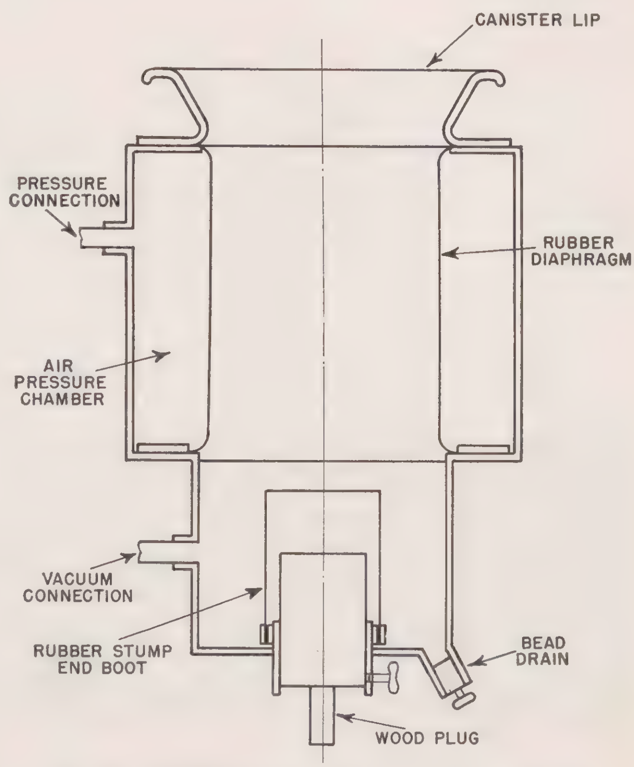


Fig. 127. Canister assembly for the dilatancy machine.

was maintained throughout this procedure until the plaster had hardened. After the plaster had set, the vacuum was released, the combined replica and mandrel were removed from the canister, and the rubber bag was stripped from the replica.

To prepare sockets from the replica, a winding machine and baking oven for the plastic were constructed. Gauze bandage rolls, one inch wide, were unrolled, soaked in Selectron 5003 resin, and wound onto the lacquer coated replica until a uniform layer had been applied. The assembly then was removed from the winding machine, sealed in Resistoflex sheeting to prevent surface oxidation and put into the heated oven for curing. After the plastic had been cured, the sheeting was stripped off and the plaster replica broken out. The laminated plastic socket which was left was then sanded, trimmed, and sized for insertion into the limb shank.

By making replicas in the dilatancy machine using different air pressures and in comparing these replicas with those shaped by hand by different technicians experienced in limb fitting, the dilatancy machine has shown itself capable of duplicating and of copying stump shapes. With suitable mechanisms for exerting localized pressures, the stump shapes can be varied from exact to round or to a triangular shape. The degree of roundness or triangulation depends entirely on the forming pressures and their distribution. If, through a basic program concerned with bearing pressures and pain of the stump, information collected could lead to the establishment of standards for a correct type of socket cross section or the amount of reduction of stump area necessary for comfort, the dilatancy process will represent a distinct advantage over present hand-molding methods of forming the socket for an artificial leg.

SUCTION SOCKET PROJECT

BACKGROUND. The suction socket method of securing an artificial leg to an above-knee stump, although the subject of U. S. patents in 1863, apparently was not used extensively until about seventy years later, when German limb makers began fitting such limbs to patients. Many successful cases were observed in Germany in the spring of 1946 by members of the Army Surgeon General's Commission on Amputations and Prostheses; in fact, the suction socket was found to be in almost universal use for above-knee amputations in the U. S. zone of occupation, which was the only zone visited. Since there were extreme variations of opinion regarding the usefulness of this method of fitting artificial legs, and since it was not altogether clear why the suction socket method was not used more widely in this country, the Committee thought it expedient to explore the problem.

In the genesis of this research problem, the Committee was fortunate in having Dr. Rufus H. Alldredge, staff surgeon and a member of the European Commission, and Mr. Carlton E. Fillauer, staff limb fitter, to delineate and supervise this program. Mr. Eugene F. Murphy, staff engineer, also gave valuable assistance to this project. Later Mr. Lorrin H. Madsen joined the staff as limb fitter to aid in the program and on his resignation was succeeded by Mr. C. Richard Fadely. Upon Dr. Alldredge's resignation to return to private practice, he became orthopedic consultant to the Committee.

The responsibility for the suction socket program was then transferred to and accepted by the group working on prosthetics research at the University of California in Berkeley. The staff concerned primarily with completing the program are Mr. Fadely and Mr. Jim C. McKennon, limb fitters, Dr. Verne T. Inman, orthopedic consultant and member of the Medical School faculty in San Francisco, Professor Howard D. Eberhart, engineer in general charge, and Mr. David Brant, administrative assistant in charge of records and correspondence.

Having secured the cooperation of a number of limb manufacturers in various parts of the country in this research problem, the Committee has amassed considerable data relating particularly to the factors contributing to the successful fitting and wearing of the prosthesis. By experimenting in several geographical locations it hoped to determine any possible adverse effects of climate on the wearing of such limbs. Each limb manufacturer engaged in the work has as consultant an orthopedic surgeon appointed by the Committee on Artificial Limbs.

PROJECT. The only apparent difference between a suction socket leg and the conventional above-knee leg is the elimination of the pelvic hinge and all suspension harness. The leg is held on by a small amount of negative pressure, or suction, created in the carefully fitted socket by the action of the stump. The socket must fit snugly in order to maintain an air seal, but should not be tight enough to restrict the muscles of the stump which now must be used to control all motions of the leg. No sock is worn on

the stump. If the socket is fitted properly, there is little piston action of the flesh moving up and down adjacent to the side wall of the socket.

Without the pelvic joint, the alignment of the entire leg becomes more important and must be accurate for good results. While this should be no deviation from the conventional type fitting, poor alignment sometimes has been compensated for in part by location and adjustment of the pelvic joint.

In Fig. 128, a thin sock is used to pull the fleshy portions of the stump into the socket. The sock is pulled off the stump and out of the socket through the hole normally occupied by a valve. After the stump has been seated and is comfortable, the valve is screwed into the hole while normal weight is on the leg, thus preventing air from entering the socket. Either a plug type valve with manual release of suction or pressure, or a valve which automatically exhausts air at a definite positive pressure may be used. Note in Fig. 128(d), that the leg is supported without a pelvic band or other suspension.

Weight has been supported mainly on the ischial tuberosity for the majority of subjects fitted so far. A few have been fitted with plug type of fit with apparent success.

Elimination of the pelvic band and hinge gives the amputee more freedom and less interference with clothing. With the piston action of the stump largely eliminated, the prosthesis seems to feel and react more like an integral part of the body and is capable of being controlled more actively.

The suction socket is not a method of fitting to be recommended where the conventional socket has been unsuccessful. Spur growths on the bones, sensitive nerve endings, and bad scars will be handicaps with both types of socket. Muscular, cylindrical stumps of medium or long length are suited best to the use of a suction socket. Short stumps and bad scars cause difficulty in making a seal hold the partial vacuum. It is recommended strongly that X rays be made and an orthopedic surgeon be consulted before using a suction socket.

No detrimental effects due to the wearing of a correctly fitted suction socket have been found thus far. Poorly fitted sockets have caused sores, as have properly fitted sockets with poor alignment of the rest of the leg. But this is true of all artificial legs. The small amount of negative pressure required to hold the leg on has evidenced no measurable change in blood circulation, but in some cases, has caused moderate edema on the distal end of the stump which disappeared, possibly because of body adjustment, in a few weeks. Edema may be eliminated by a small cushioning pad in the bottom of the socket which produces a slight amount of positive pressure on the affected area. Because the stump muscles are used

(a) Thin sock placed on stump. *(b) Pulling off stump sock to smooth flesh in the socket.* *(c) Valve inserted with weight on the leg.* *(d) Leg supported without pelvic band or other suspension.*

Fig. 128

more actively in the suction socket, increased development generally occurs which requires an enlargement of the socket.

The use of the suction socket method of fitting below-knee amputees is not indicated at this time.

Although results thus far obtained in selected cases have been highly encouraging, it should be made clear that this method is yet in the experimental stage and that it has not become standardized. The Committee emphasizes that it has not approved the method for general use. Cases to be fitted should be selected only under the supervision of a competent physician, and patients should be assured that the limb fitter is informed thoroughly about the fitting and construction of suction sockets.

Although all technical information in possession of the Committee is being made available to the limb manufacturers, the final results of this exploratory problem will not become available until the early part of 1948.

CINEPLASTIC METHOD IN UPPER EXTREMITY AMPUTATIONS

BACKGROUND. On the return of the Army Surgeon General's Commission on Amputations and Prostheses from Europe, members of the Commission concurred in a recommendation that cineplastic surgery be approved for properly selected upper extremity amputees in this country. They suggested also that surgery be performed on a number of carefully controlled cases and that an effort be made to perfect suitable prostheses for such cases. Since the return of this Commission in the spring of 1946, there has been much renewed interest in this cineplastic method.

This method consists of surgically constructing skin-lined canals, or muscle motors, through the distal parts of the remaining muscles of the stump. Usually two such muscle motors are constructed: one tunnel is placed through the flexor group of muscles and the other through the extensor group. They may be constructed either above or below the elbow. After healing of the skin-lined tunnels which were constructed to run transversely through the middle of the muscle mass, a peg is inserted through each tunnel and by active contraction of the muscles through which the peg passes, the peg is moved upward or proximally on the prosthesis. This motion corresponds to the same motion which these muscles performed before amputation: when the flexor group of muscles contracts, the peg, being connected from both ends to the artificial hand, causes closure of the hand; when the extensor group is contracted, the hand is opened by the reverse process. In some cases only one motor is used and the tunnel is placed through the flexor group of muscles either above or below the elbow. In the prosthesis used for this case a spring in the artificial hand takes the place of the extensor motor muscle and holds the hand in the open position until it is closed by the action of the flexor muscle motor.

Another type of skin tunnel sometimes is constructed which does not pass through the muscle and is used purely for the purpose of holding the prosthesis in place. This holding tunnel, or fixation canal, can be used on the flexor surface of a very short forearm stump where the functioning muscle motor is through the biceps above the elbow. It can be used also on very short above-elbow stumps in connection with the pectoralis motor.

Although Vanghetti of Italy first conceived the idea of cineplasty just before the turn of the century, there had been little encouraging evidence that this method was practical until the members of the Surgeon General's Commission saw the results of the work of Dr. Max Lebsche in Munich. Lebsche, a former student of Sauerbruch, had developed, during the previous three years, new criteria in the selection of cases, progress in the location of tunnels, and a more successful attack in the surgical technique, all of which had resulted in improvement of function of the muscle motors. Although the cineplastic prosthesis used in Germany was crude and the hand had only the function of pinch, the Commission was favorably impressed with the results obtained, chiefly because of the unusually good function of the muscle motors. It was the consensus of the members that if a prosthesis could be correspondingly improved, the cineplastic method, using Lebsche's surgical principles, would be suitable for trial in this country for certain selected upper extremity amputees.

There are still many surgeons in Germany who do not consider the cineplastic method worth while because of the many failures after the first World War. Dr. Lebsche, however, has obtained results which, purely from the surgical standpoint, go far toward refuting the unfavorable criticisms of the cineplastic procedures, and it should be noted that other surgeons, even in Germany, were neither aware of nor using this improved surgical principle. In the United States the cineplastic method of Sauerbruch

Fig. 129. Bilateral below-elbow amputee wearing German made cineplastic prostheses.

had been carried on to a limited extent, but the results had not been convincing to those interested in the functional rehabilitation of amputees.

PROJECT. Dr. Rufus H. Alldredge, staff surgeon, spent several weeks with Professor Lebsche studying all phases of the surgery and prostheses. Artificial arms of the various types for cineplastic patients were sent to this country and arrangements were made for four German cineplastic amputees to visit the United States for the purposes of working with the subcontractors of the Committee on Artificial Limbs on the improvement of the prosthesis, and of promoting interest in the program among arm amputees. Three of these amputees arrived in this country in August, 1946, and after several demonstrations proving their dexterity before interested orthopedic surgeons, they were sent to the west coast for inspection and testing of their prostheses and muscle motors. The fourth amputee arrived shortly thereafter. In February, 1947, two additional German arm amputees were sent to this country. Both were bilateral above-elbow cases; one with two pectoral muscle tunnels because of very short stumps; the other with two biceps and two triceps tunnels. The German amputee, shown in Fig. 129, is a bilateral below-elbow amputee having a flexor and extensor muscle motor in each arm. His artificial arms and hands are of German make.

With the arrival of these German amputees in this country, considerable data relating to muscle length in active tension were compiled. Results of these findings can be found under the portion of this report on the University of California at Berkeley. From these data and from results obtained from the hand studies at the University of California at Los Angeles, work toward a suitable prosthesis was undertaken by the Sierra Engineering Company and by Vard, Inc. Developments under all of these subcontracts can be found elsewhere in this report.

As a result of the interest shown by amputees in this country after having witnessed the dexterity and prowess with which the visiting German cineplastic amputees manipulated their prostheses, Dr. Alldredge performed the cineplastic operation on three volunteer arm amputees, and Dr. Leonard T. Peterson, another member of the European Commission, operated on two. In each case the operation was successful. Although more amputees have volunteered to undergo this operation, it was thought unwise to perform any more operations until suitable prostheses have been developed.

Dr. Alldredge, in his publication "The Cineplastic Method in Upper Extremity Amputations," has pointed out an obvious and important advantage in using this method. This prosthesis (more than the conventional type arm) seems to become a part of the patient and because the amputee has a more active control of the arm and hand it becomes easier to use and more functional. Patients who have had good results surgically have been enthusiastic about the cineplastic method.

An obvious disadvantage to this method is that great care must be exercised in the choice of the patient, in the location of the muscle tunnels, and in the post-operative rehabilitation of the patient. Mistakes along these lines inevitably result in failure regardless of the mechanical perfection of the prosthesis. The meticulous care with which the muscle tunnels must be cleansed with alcohol and powdered at frequent intervals, particularly in warm climates, might be pointed out as another disadvantage. There is danger, if proper care is neglected, that the skin in the tunnels may break open and be rendered incapable of further use.

While great strides have been made in the improvement of the cineplastic prosthesis, the lack of a perfected production model remains one of the greatest disadvantages of this method. While a good start toward this end has been made by the combined efforts of several subcontractors working under the auspices of the Committee, there is yet much to be desired in a prosthesis developed for the cineplastic amputee.

Printed by Neely Printing Company, Inc., Chicago